FIG.1

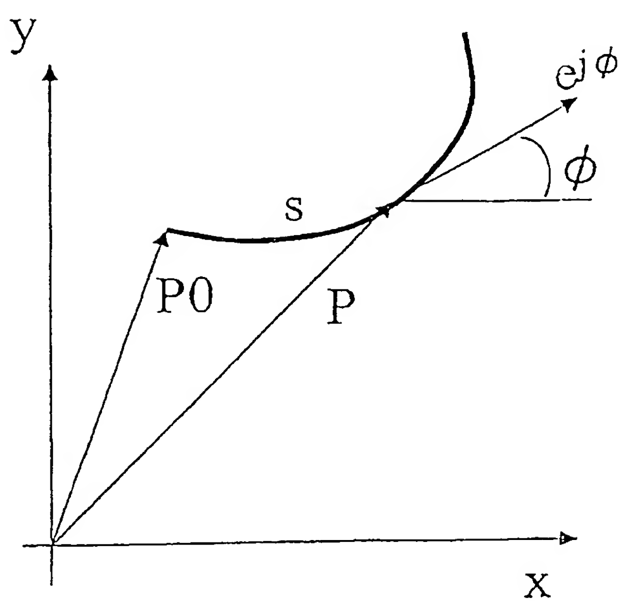


FIG.2

$$0 \le S = \frac{s}{h} \le 1$$

$$P(S) = P_0 + h\int_0^S (\cos\phi + j\sin\phi)\,dS$$

$$\phi(S) = \phi_0 + \phi v S + \phi u S^2$$

P0 : COORDINATE OF STARTING POINT
ϕ : ANGLE MADE BETWEEN TANGENTIAL DIRECTION AND x-AXIS
h : CURVE LENGTH
s : DISTANCE MOVED FROM STARTING POINT
S : CURVE LENGTH VARIABLE
ϕ_0, ϕv, ϕu : $(const)$

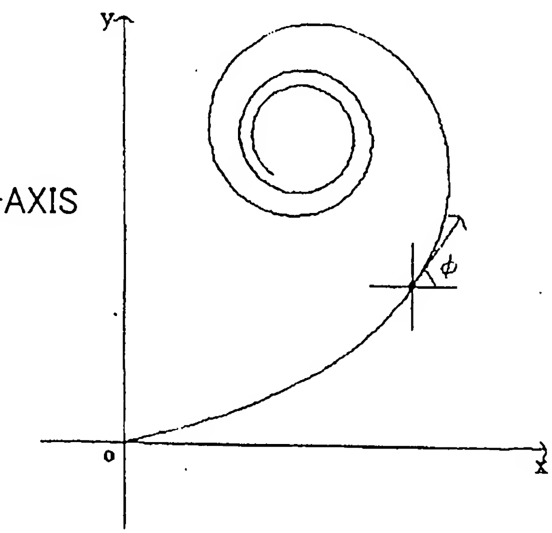


FIG.3

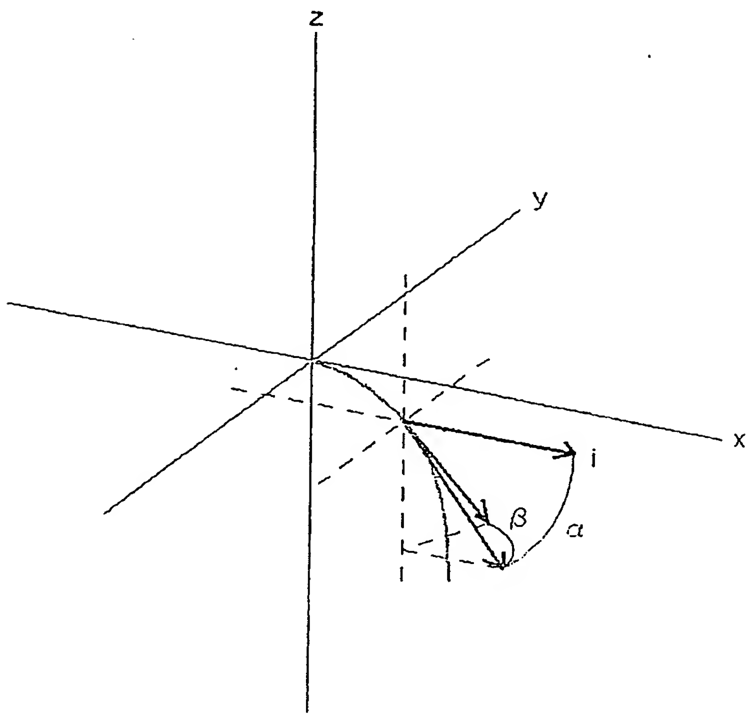


FIG.4

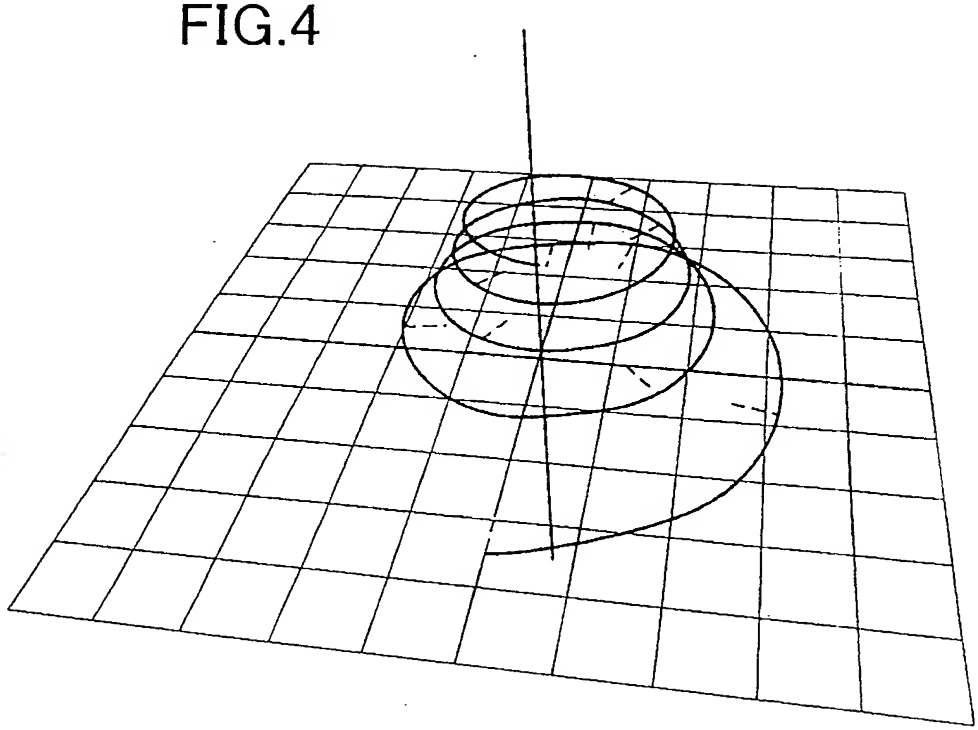


FIG.5

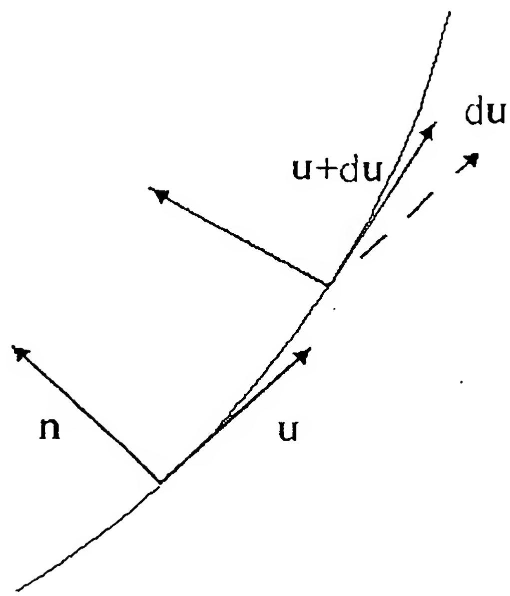


FIG.6

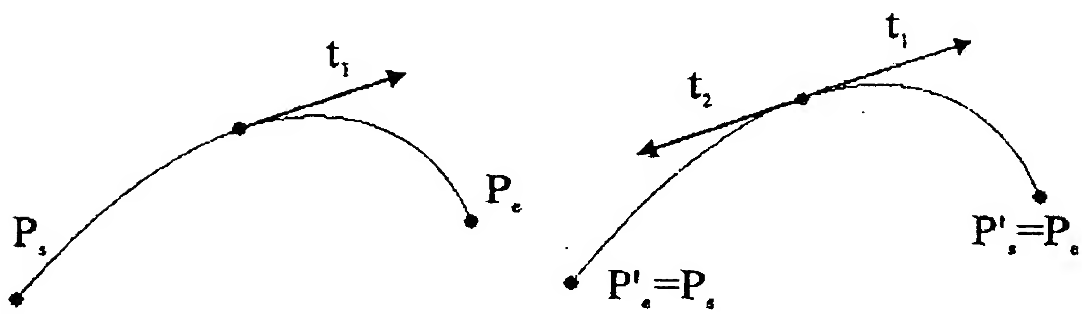


FIG.7

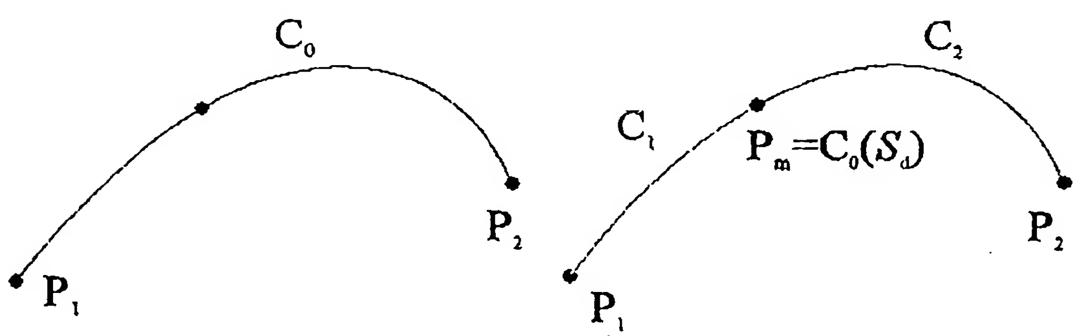


FIG.8

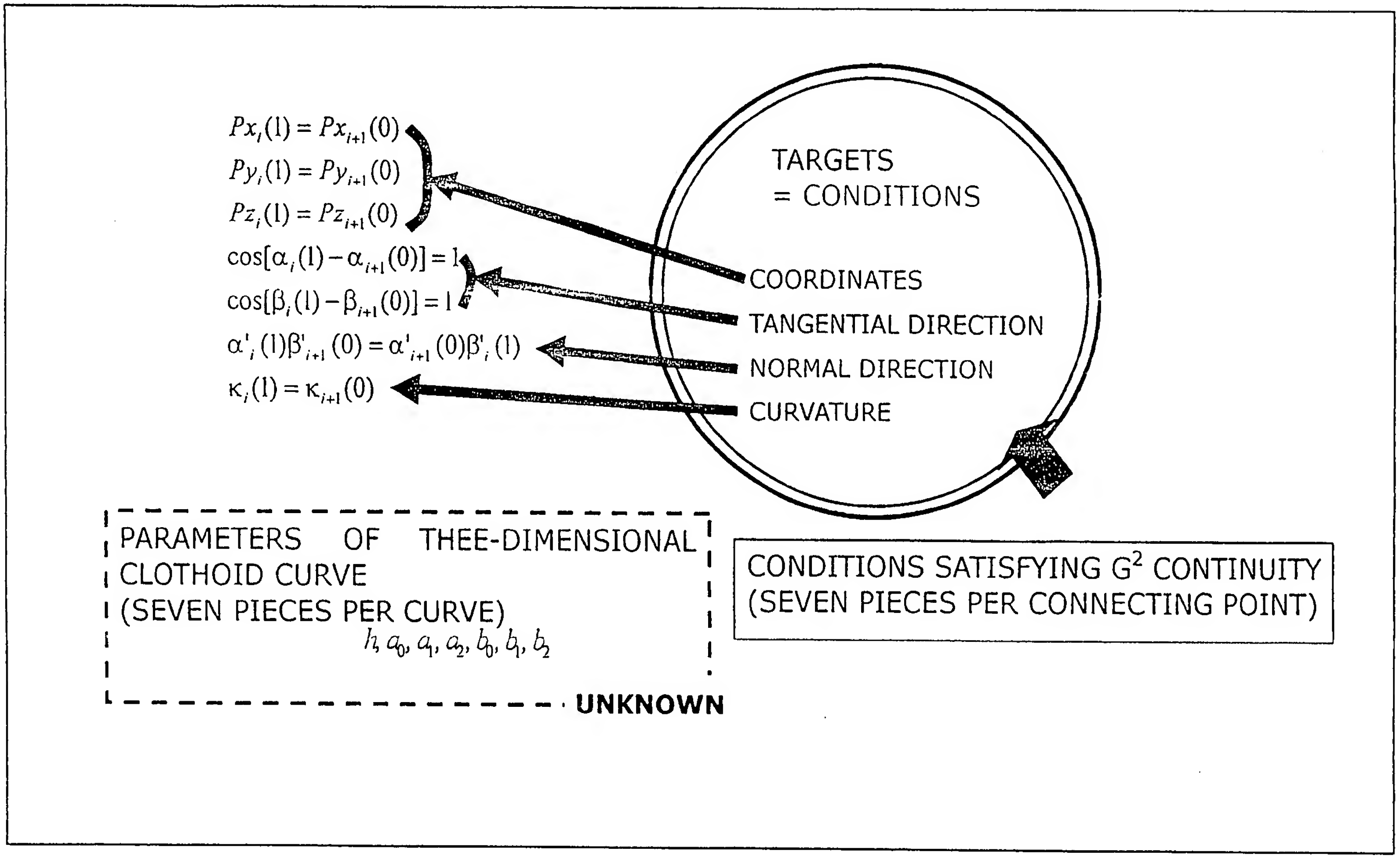

$Px_i(1) = Px_{i+1}(0)$
$Py_i(1) = Py_{i+1}(0)$
$Pz_i(1) = Pz_{i+1}(0)$
$\cos[\alpha_i(1) - \alpha_{i+1}(0)] = 1$
$\cos[\beta_i(1) - \beta_{i+1}(0)] = 1$
$\alpha'_i(1)\beta'_{i+1}(0) = \alpha'_{i+1}(0)\beta'_i(1)$
$\kappa_i(1) = \kappa_{i+1}(0)$
TARGETS
= CONDITIONS
COORDINATES
TANGENTIAL DIRECTION
NORMAL DIRECTION
CURVATURE
PARAMETERS OF THEE-DIMENSIONAL CLOTHOID CURVE
(SEVEN PIECES PER CURVE)
$h, a_0, a_1, a_2, b_0, b_1, b_2$
UNKNOWN
CONDITIONS SATISFYING G^2 CONTINUITY
(SEVEN PIECES PER CONNECTING POINT)

FIG.9

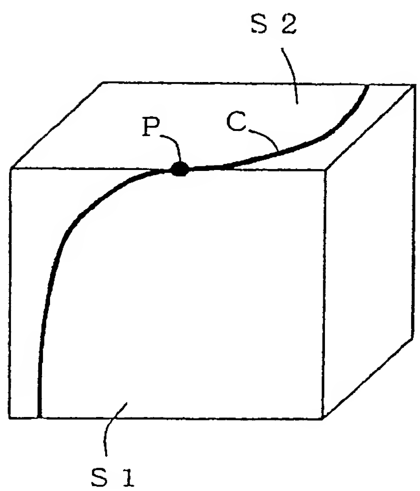


FIG.10

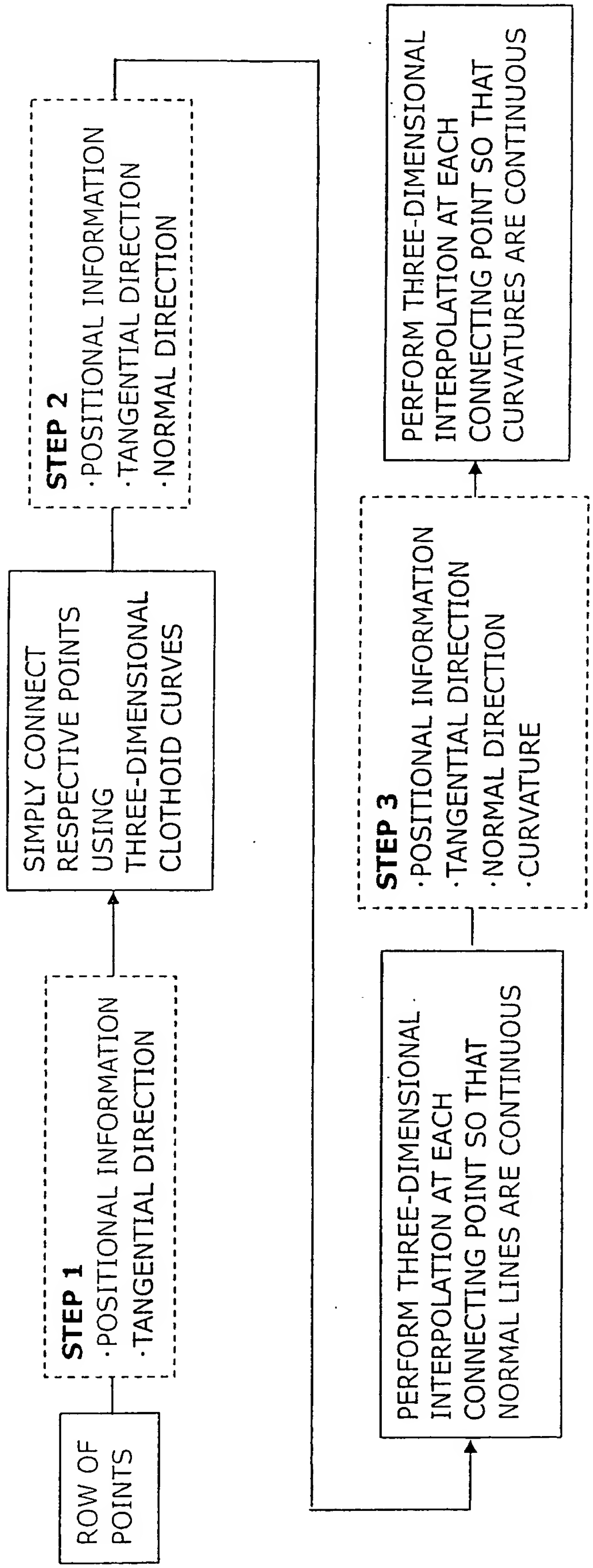

ROW OF POINTS
STEP 1
·POSITIONAL INFORMATION
·TANGENTIAL DIRECTION
SIMPLY CONNECT RESPECTIVE POINTS USING THREE-DIMENSIONAL CLOTHOID CURVES
STEP 2
·POSITIONAL INFORMATION
·TANGENTIAL DIRECTION
·NORMAL DIRECTION
PERFORM THREE-DIMENSIONAL INTERPOLATION AT EACH CONNECTING POINT SO THAT NORMAL LINES ARE CONTINUOUS
STEP 3
·POSITIONAL INFORMATION
·TANGENTIAL DIRECTION
·NORMAL DIRECTION
·CURVATURE
PERFORM THREE-DIMENSIONAL INTERPOLATION AT EACH CONNECTING POINT SO THAT CURVATURES ARE CONTINUOUS

FIG.11

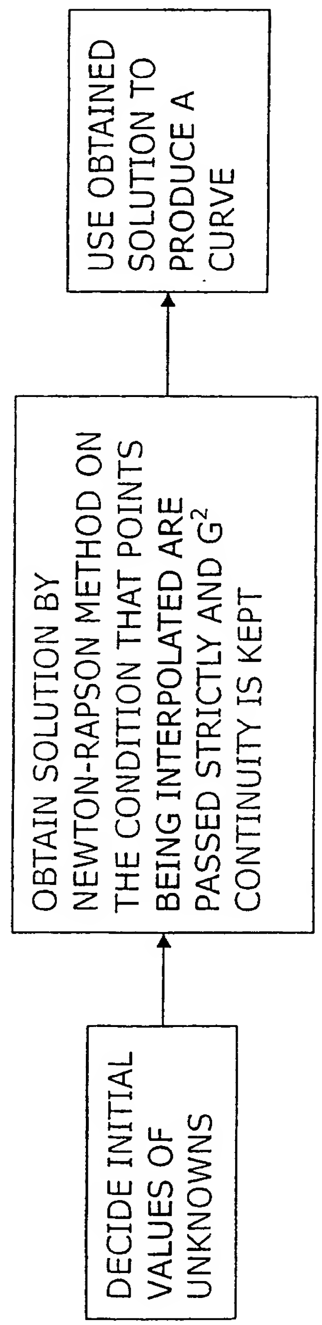

DECIDE INITIAL VALUES OF UNKNOWNS
OBTAIN SOLUTION BY NEWTON-RAPSON METHOD ON THE CONDITION THAT POINTS BEING INTERPOLATED ARE PASSED STRICTLY AND G2 CONTINUITY IS KEPT
USE OBTAINED SOLUTION TO PRODUCE A CURVE

FIG.12

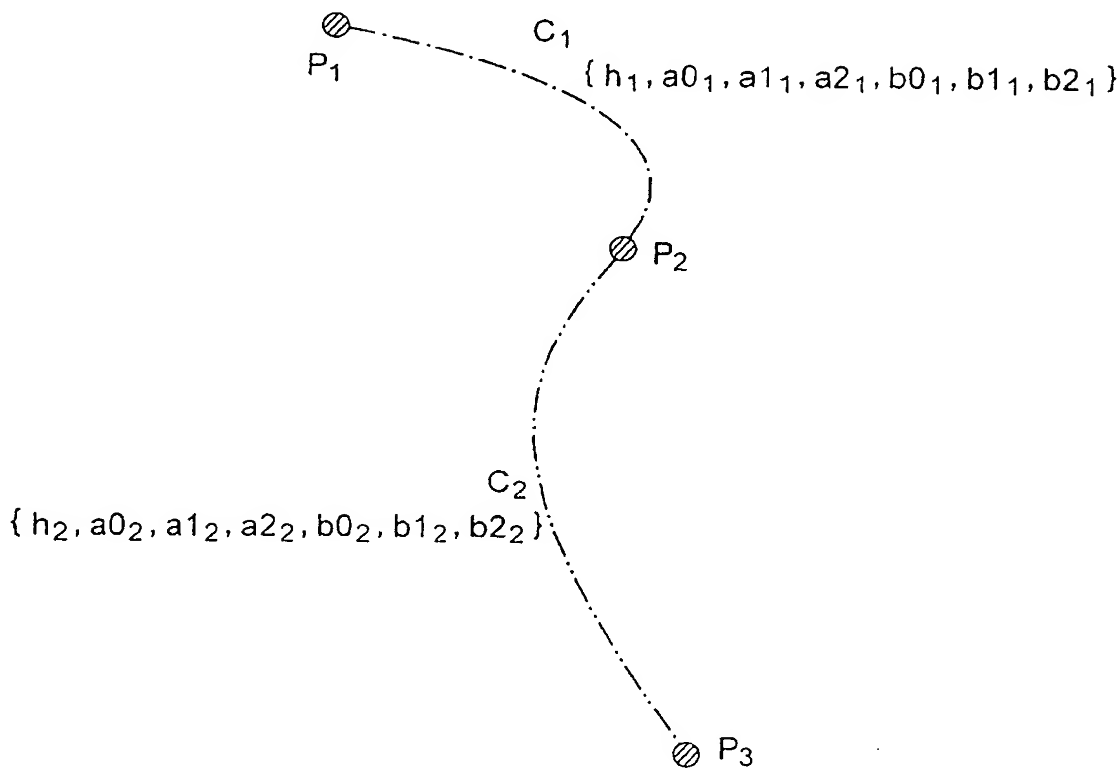

P_1
C_1
$\{h_1, a0_1, a1_1, a2_1, b0_1, b1_1, b2_1\}$
P_2
C_2
$\{h_2, a0_2, a1_2, a2_2, b0_2, b1_2, b2_2\}$
P_3

FIG.13

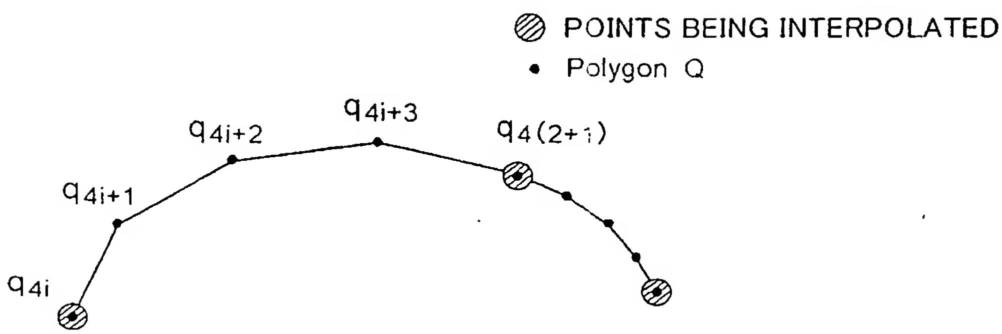
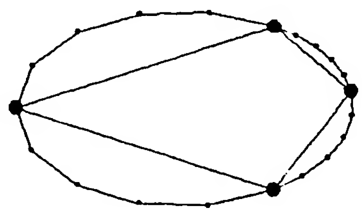

POINTS BEING INTERPOLATED
Polygon Q
q_{4i+3}
q_{4i+2}
$q_{4(2+1)}$
q_{4i+1}
q_{4i}

FIG.14



$P = \{\mathbf{p}_0, \ldots, \mathbf{p}_{n-1}\}$

$Q = \{\mathbf{q}_0, \ldots, \mathbf{q}_{n-1}\}, \quad P \subset Q$

● Polygon

P

$FrenetFrame\{\mathbf{q}_i, \mathbf{t}_i, \mathbf{b}_i, \mathbf{n}_i\}$

$$\mathbf{t}_i = \frac{\mathbf{q}_{i+1} - \mathbf{q}_{i-1}}{\left\|\mathbf{q}_{i+1} - \mathbf{q}_{i-1}\right\|}$$

$$\mathbf{b}_i = \frac{(\mathbf{q}_{i-1} - \mathbf{q}_i) \times (\mathbf{q}_{i+1} - \mathbf{q}_i)}{\left\|(\mathbf{q}_{i-1} - \mathbf{q}_i) \times (\mathbf{q}_{i+1} - \mathbf{q}_i)\right\|}$$

$$\mathbf{n}_i = \mathbf{b}_i \times \mathbf{t}_i$$

$$\kappa(q_{i-1}, q_i, q_{i+1}) = \frac{2\left\|(q_{i+1} - q_i) \times (q_{i-1} - q_i)\right\|}{\left|\mathbf{q}_{i+1}\mathbf{q}_i\right|\left|\mathbf{q}_{i-1}\mathbf{q}_i\right|\left|\mathbf{q}_{i+1}\mathbf{q}_{i-1}\right|}$$

$$\mathbf{k}_i = \kappa_i \mathbf{b}_i = \frac{2}{\gamma_i}(q_{i+1} - q_i) \times (q_{i-1} - q_i)$$

q: COORDINATE

t : UNIT TANGENTIAL VECTOR

b: UNIT NORMAL VECTOR

n: UNIT ACCESSORY NORMAL VECTOR

k: DISCRET CURVATURE NORMAL VECTOR

FIG.15

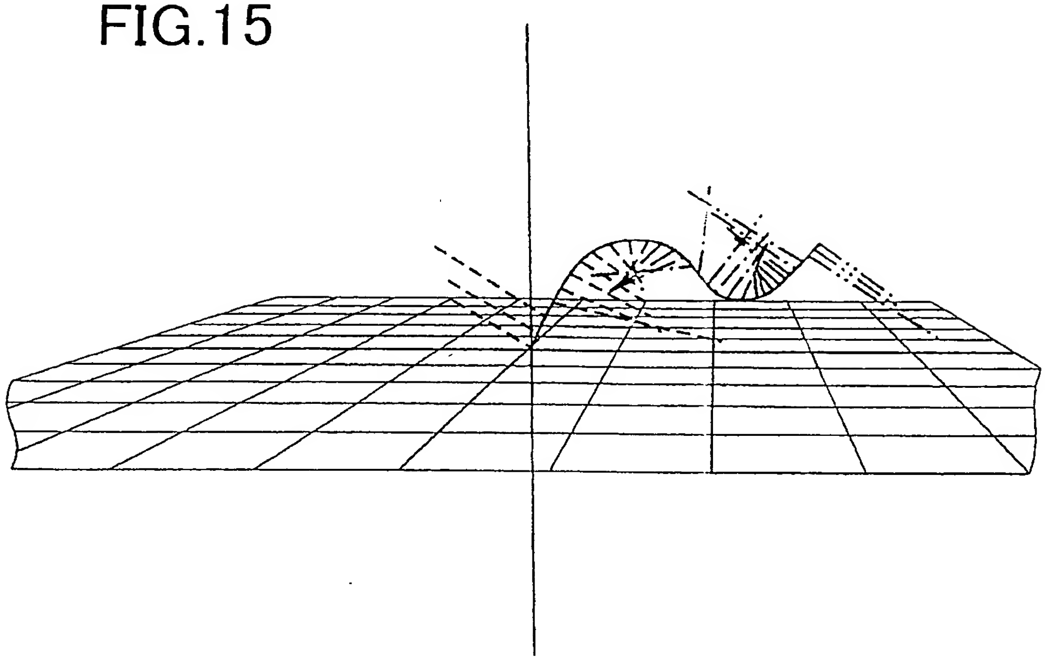


FIG.16

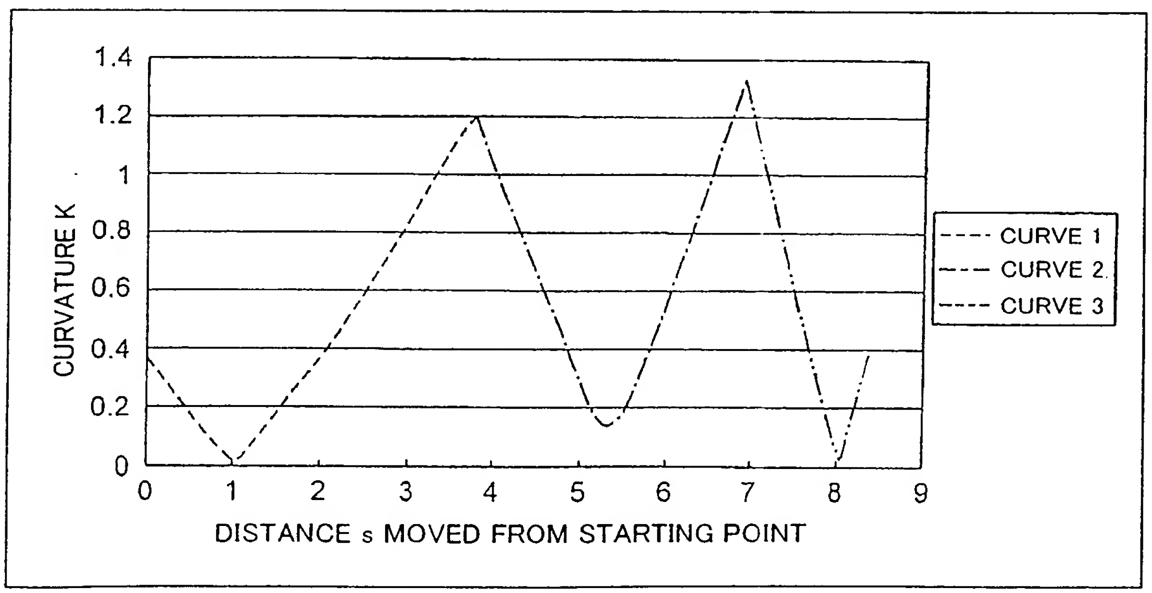

1.4
1.2
1
0.8
0.6
0.4
0.2
0
CURVATURE K
0
1
2
3
4
5
6
7
8
9
DISTANCE s MOVED FROM STARTING POINT
CURVE 1
CURVE 2
CURVE 3

FIG.17

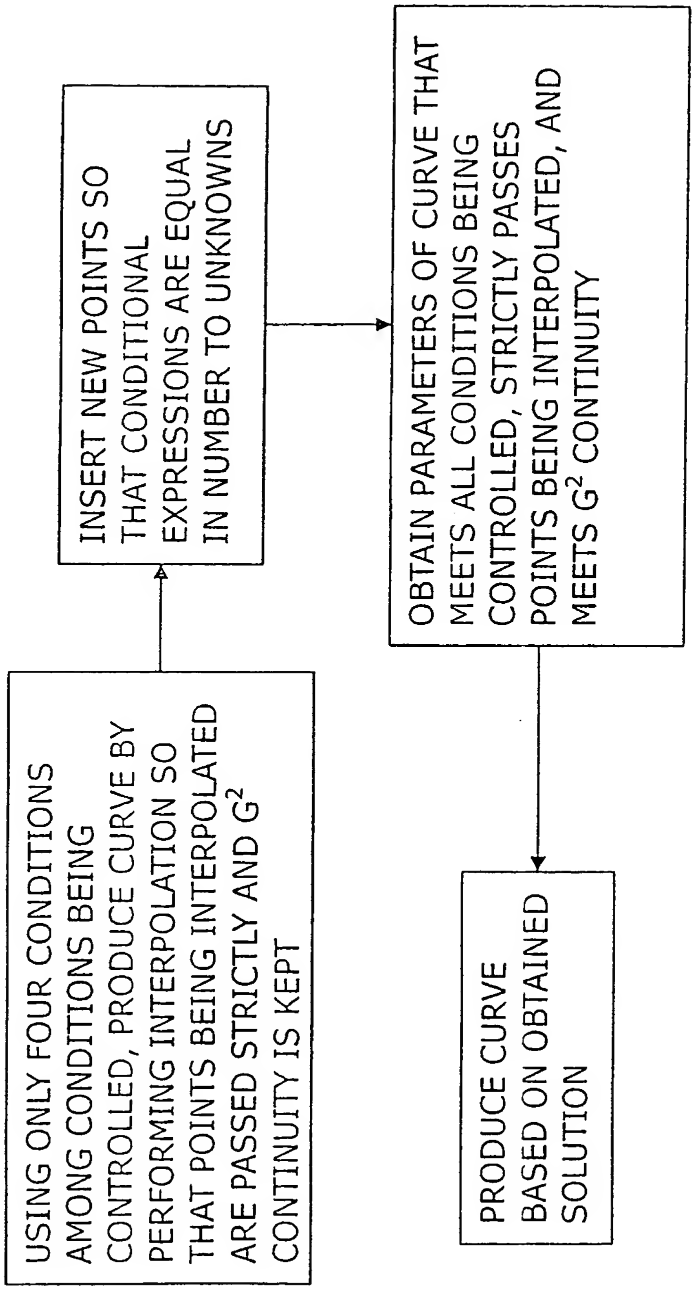

USING ONLY FOUR CONDITIONS AMONG CONDITIONS BEING CONTROLLED, PRODUCE CURVE BY PERFORMING INTERPOLATION SO THAT POINTS BEING INTERPOLATED ARE PASSED STRICTLY AND G^2 CONTINUITY IS KEPT
INSERT NEW POINTS SO THAT CONDITIONAL EXPRESSIONS ARE EQUAL IN NUMBER TO UNKNOWNS
OBTAIN PARAMETERS OF CURVE THAT MEETS ALL CONDITIONS BEING CONTROLLED, STRICTLY PASSES POINTS BEING INTERPOLATED, AND MEETS G^2 CONTINUITY
PRODUCE CURVE BASED ON OBTAINED SOLUTION

FIG.18

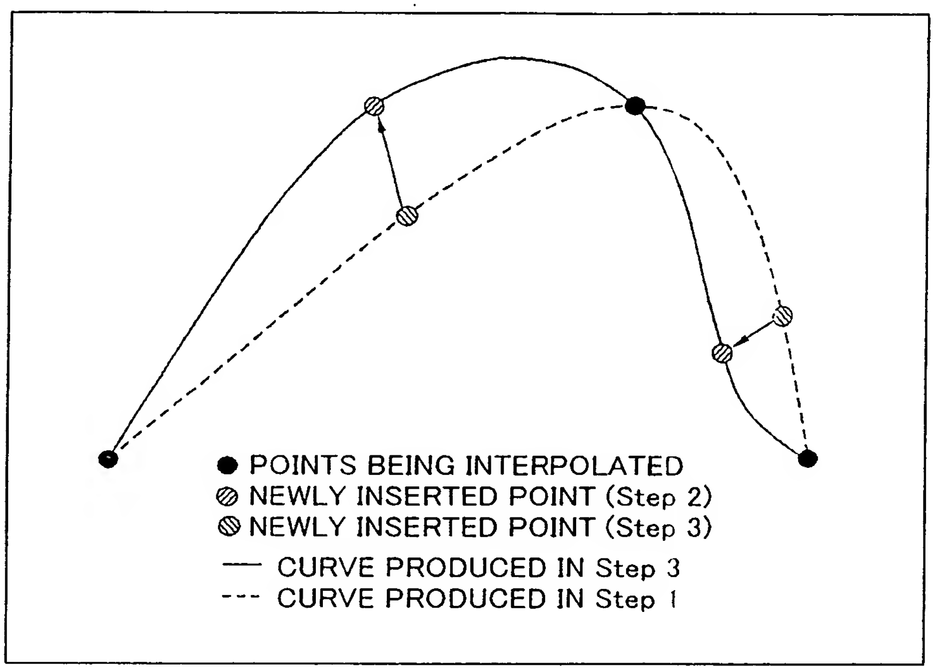

POINTS BEING INTERPOLATED
NEWLY INSERTED POINT (Step 2)
NEWLY INSERTED POINT (Step 3)
CURVE PRODUCED IN Step 3
CURVE PRODUCED IN Step 1

FIG.19

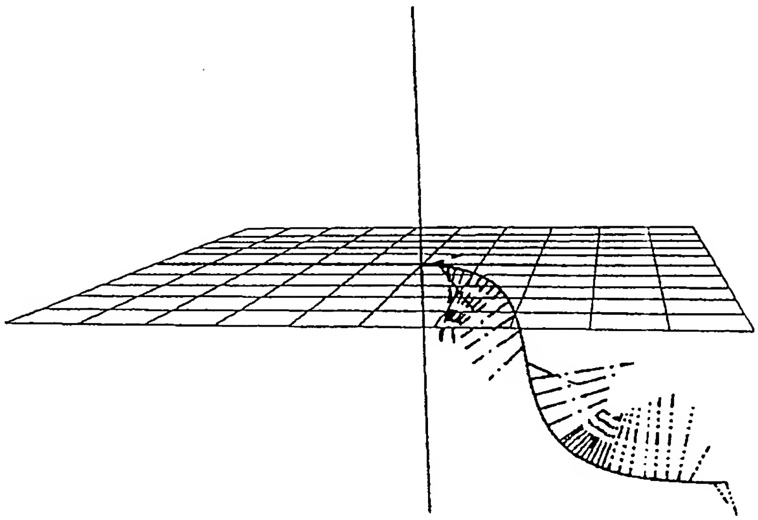


FIG.20

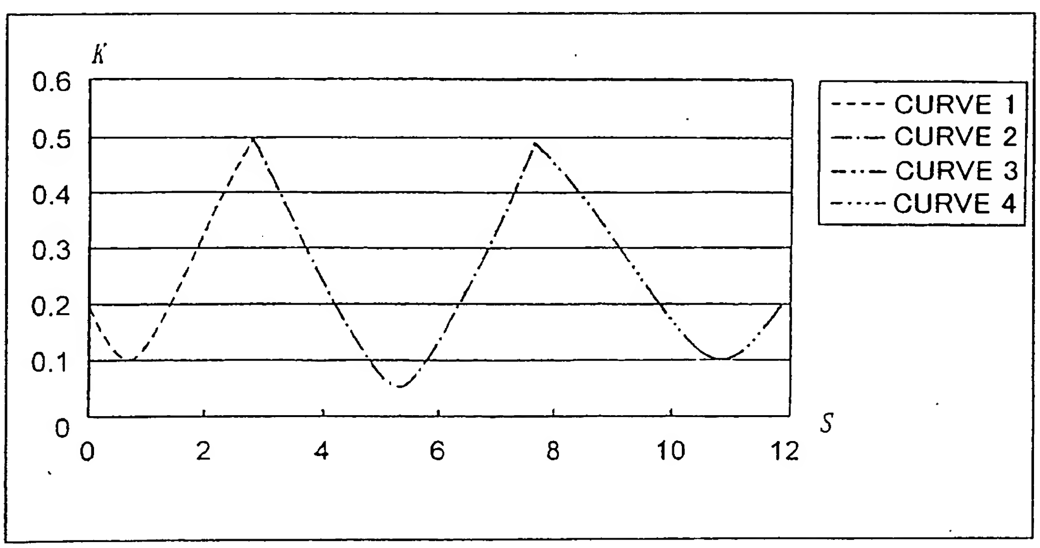


FIG.21

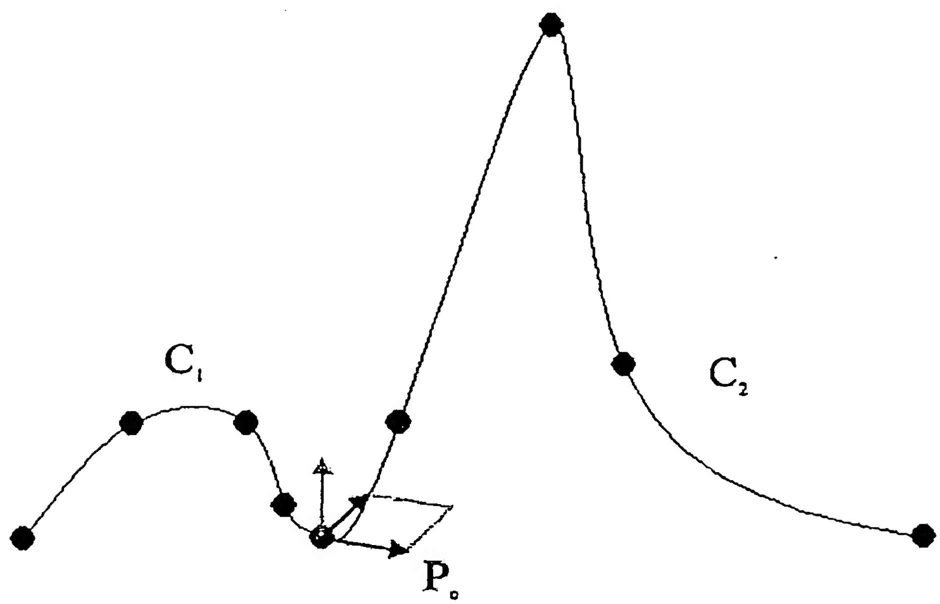


FIG.22

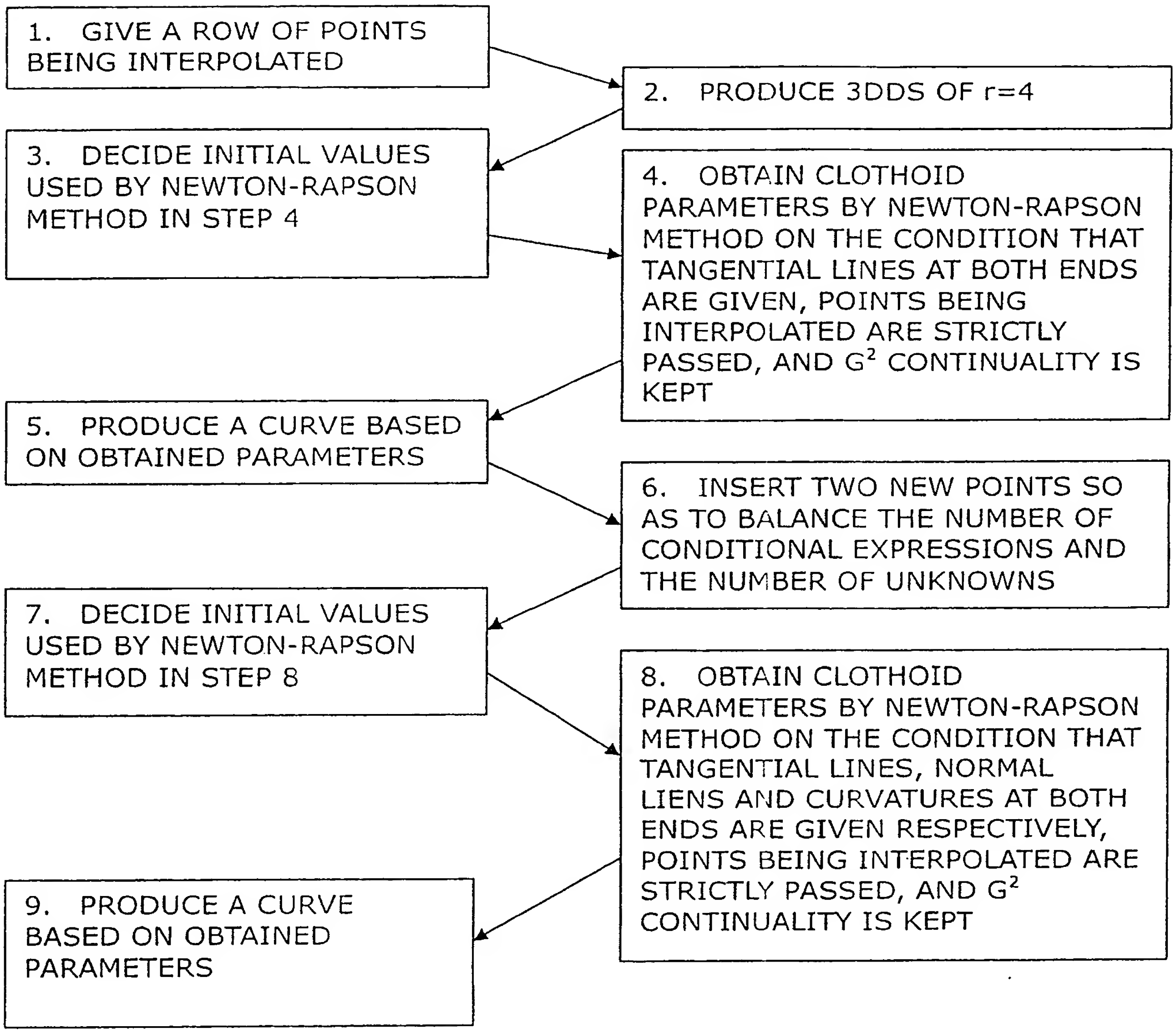

1. GIVE A ROW OF POINTS BEING INTERPOLATED
2. PRODUCE 3DDS OF r=4
3. DECIDE INITIAL VALUES USED BY NEWTON-RAPSON METHOD IN STEP 4
4. OBTAIN CLOTHOID PARAMETERS BY NEWTON-RAPSON METHOD ON THE CONDITION THAT TANGENTIAL LINES AT BOTH ENDS ARE GIVEN, POINTS BEING INTERPOLATED ARE STRICTLY PASSED, AND G2 CONTINUALITY IS KEPT
5. PRODUCE A CURVE BASED ON OBTAINED PARAMETERS
6. INSERT TWO NEW POINTS SO AS TO BALANCE THE NUMBER OF CONDITIONAL EXPRESSIONS AND THE NUMBER OF UNKNOWNS
7. DECIDE INITIAL VALUES USED BY NEWTON-RAPSON METHOD IN STEP 8
8. OBTAIN CLOTHOID PARAMETERS BY NEWTON-RAPSON METHOD ON THE CONDITION THAT TANGENTIAL LINES, NORMAL LIENS AND CURVATURES AT BOTH ENDS ARE GIVEN RESPECTIVELY, POINTS BEING INTERPOLATED ARE STRICTLY PASSED, AND G2 CONTINUALITY IS KEPT
9. PRODUCE A CURVE BASED ON OBTAINED PARAMETERS

FIG.23

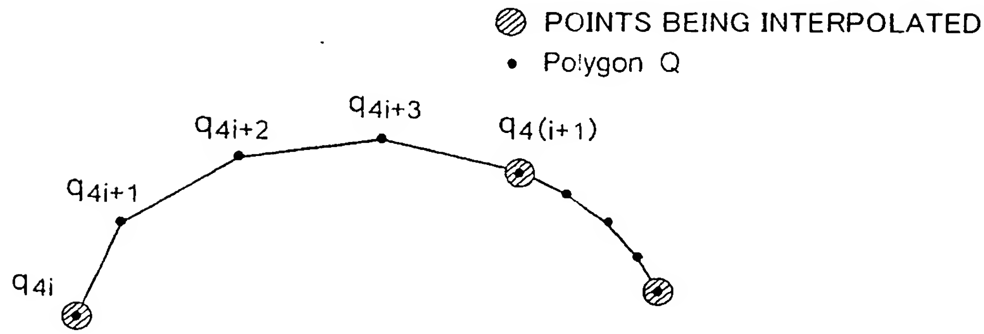

POINTS BEING INTERPOLATED
Polygon Q
q4i+2
q4i+3
q4(i+1)
q4i+1
q4i

FIG.24

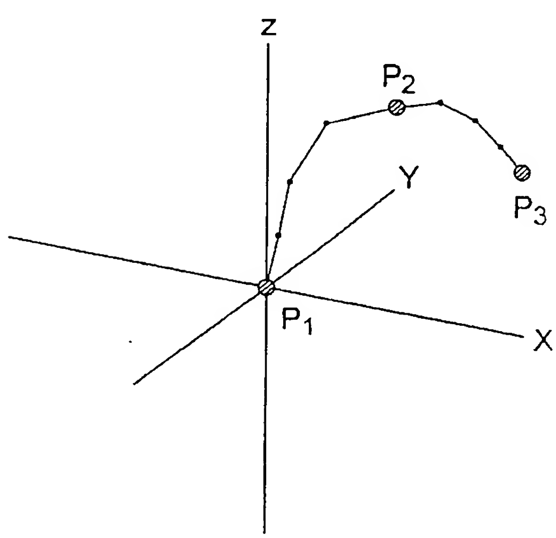

Z
P2
Y
P3
P1
X

FIG.25

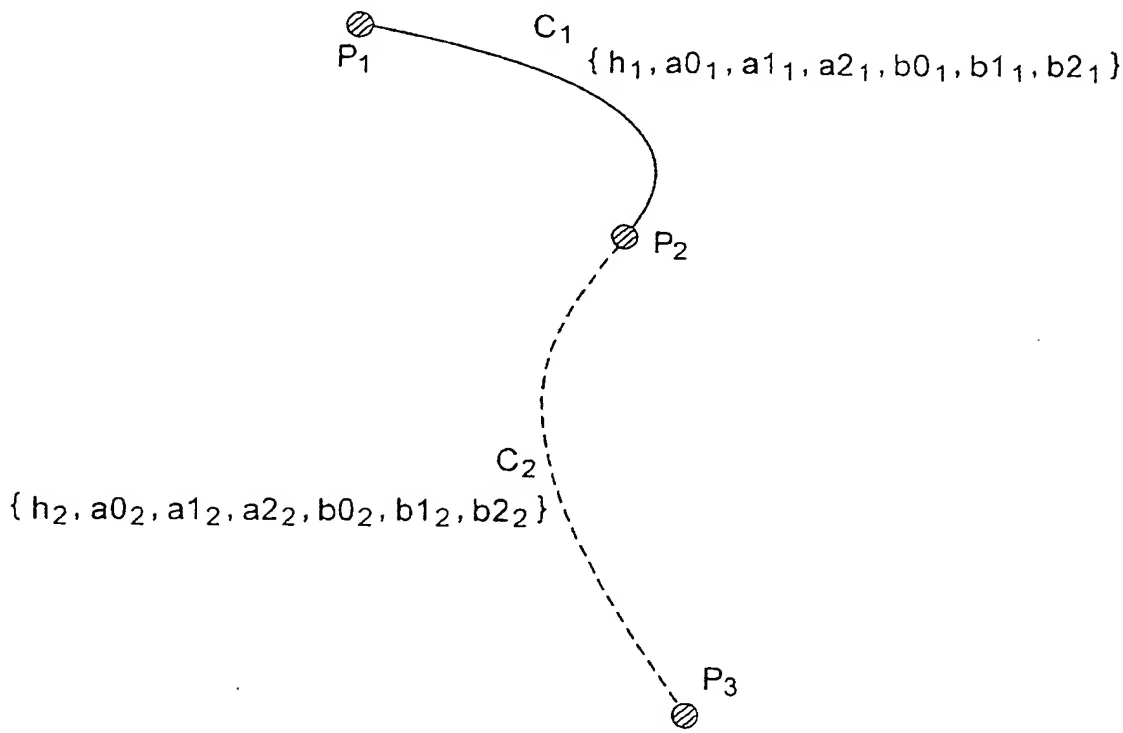

P_1
C_1
$\{h_1, a0_1, a1_1, a2_1, b0_1, b1_1, b2_1\}$
P_2
C_2
$\{h_2, a0_2, a1_2, a2_2, b0_2, b1_2, b2_2\}$
P_3

FIG.26

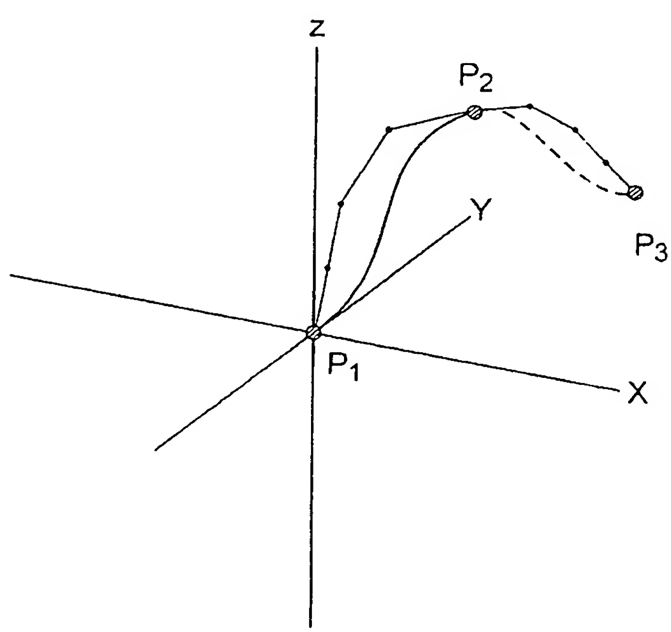

z
P_2
Y
P_3
P_1
X

FIG.27

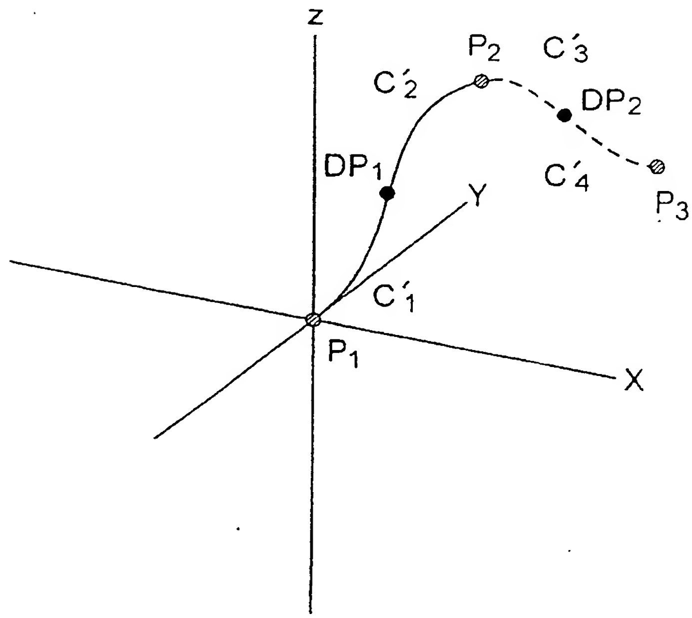


FIG.28

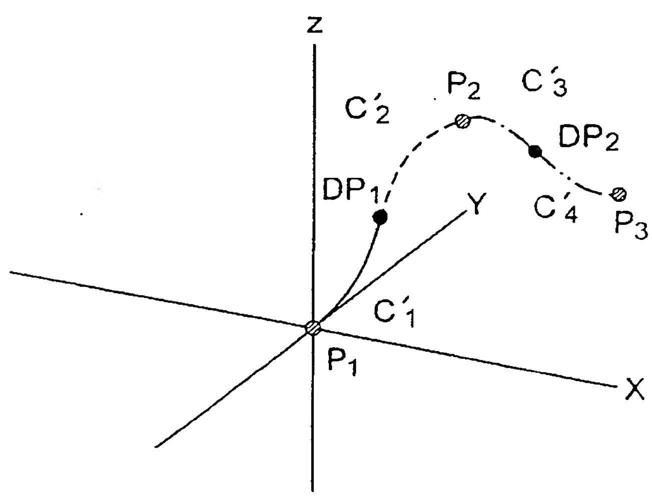


FIG.29

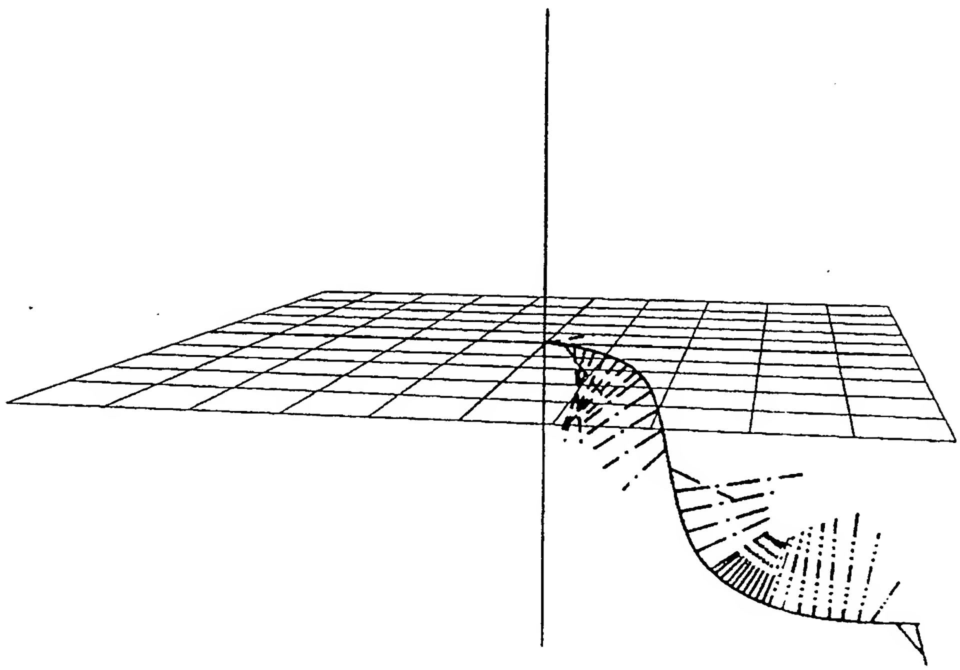


FIG.30

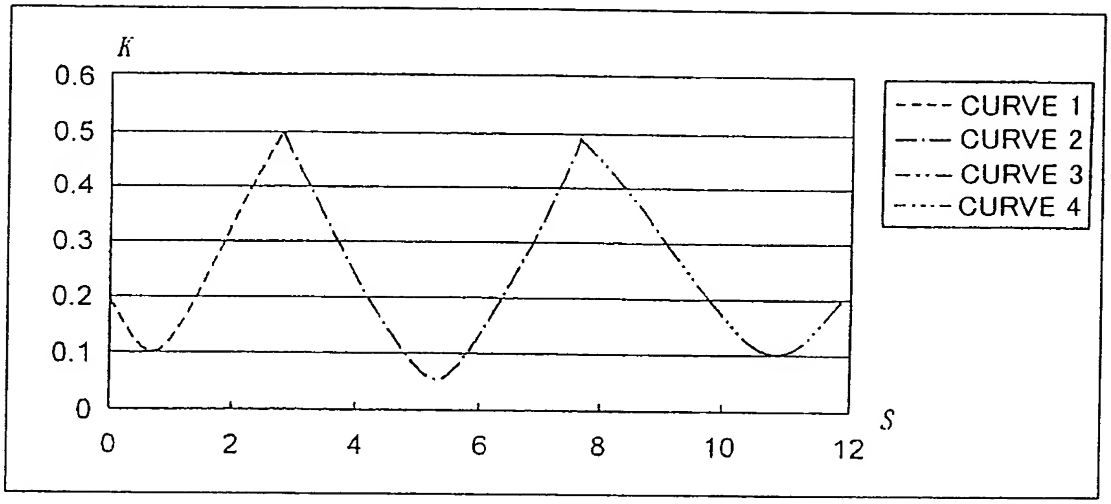

K
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
S
CURVE 1
CURVE 2
CURVE 3
CURVE 4

FIG.31

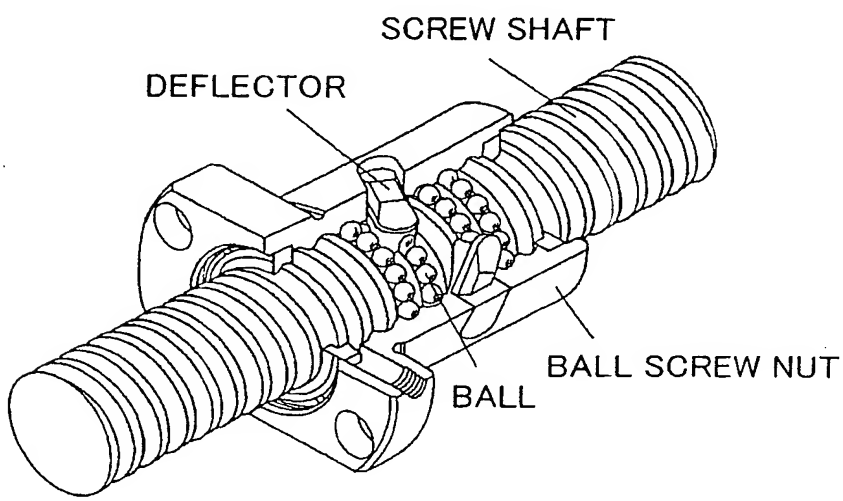

SCREW SHAFT
DEFLECTOR
BALL SCREW NUT
BALL

FIG.32

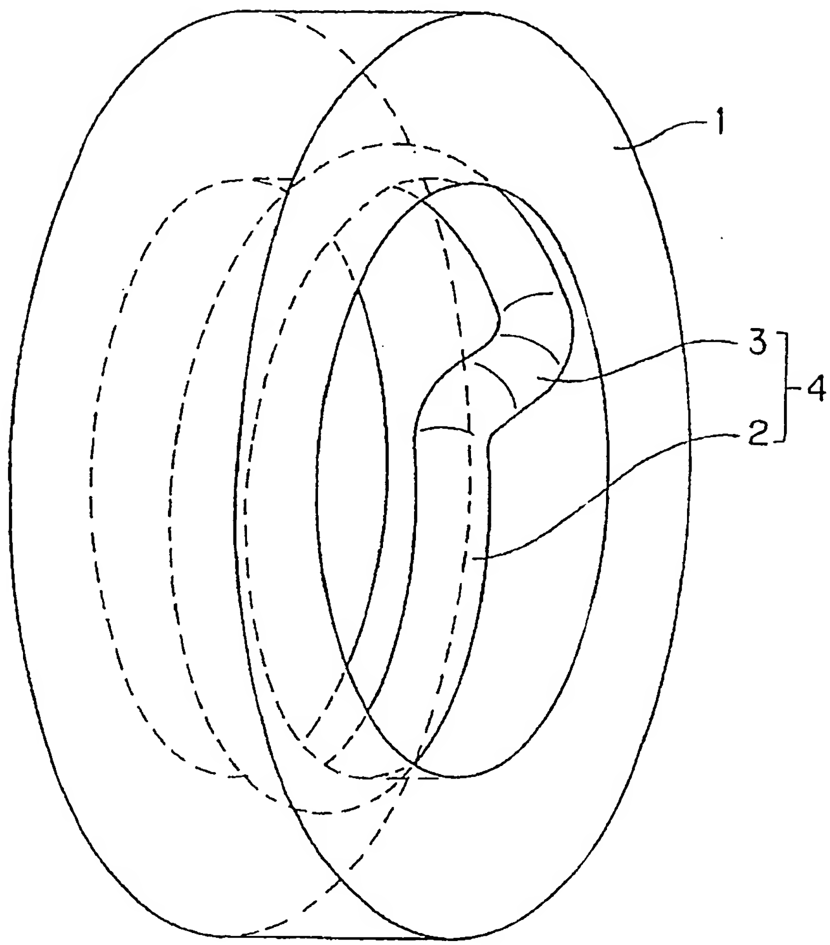


FIG.33A

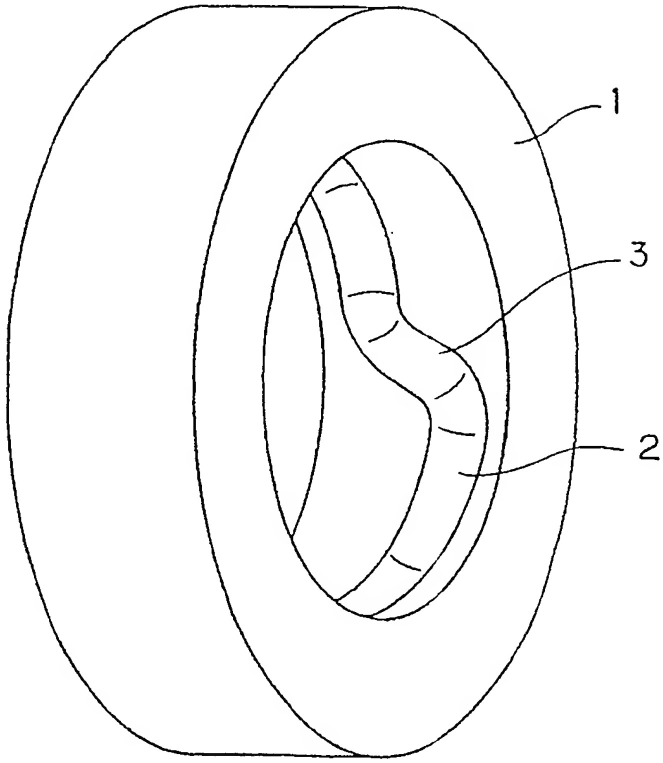


FIG.33B

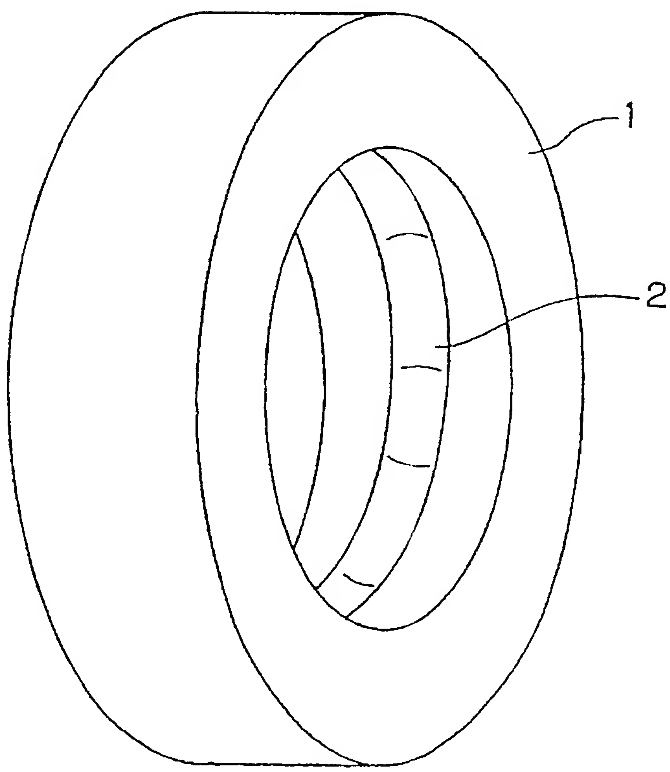


FIG.34

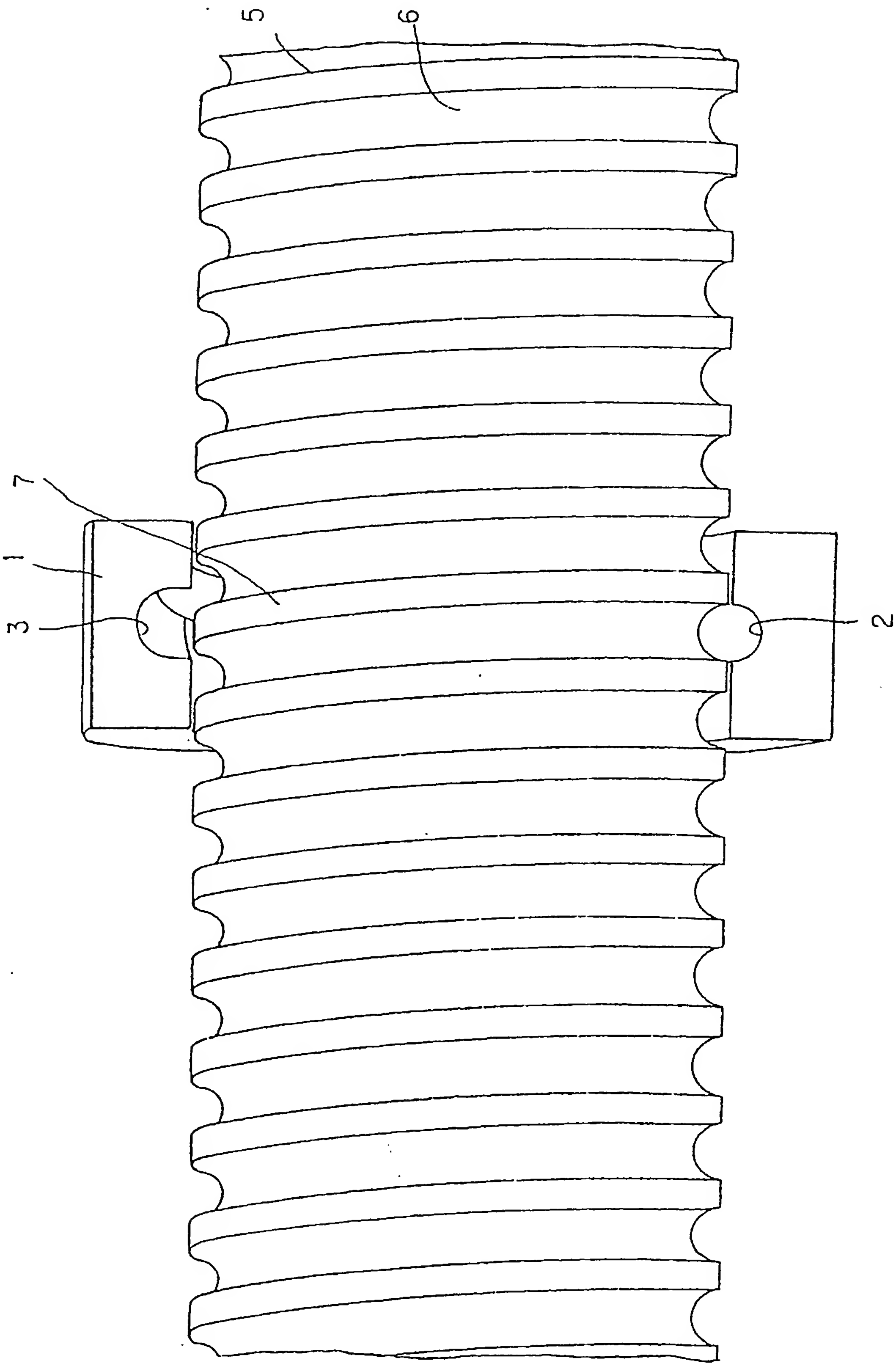


FIG.35

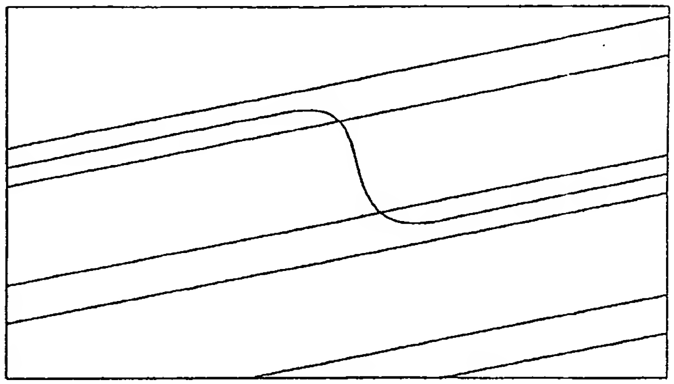


FIG.36

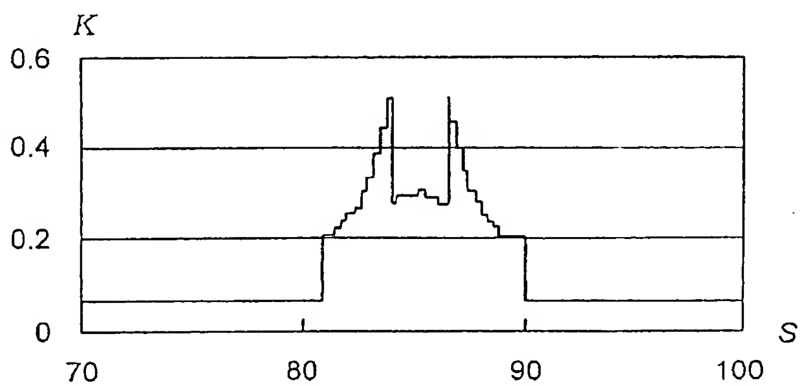


FIG.37

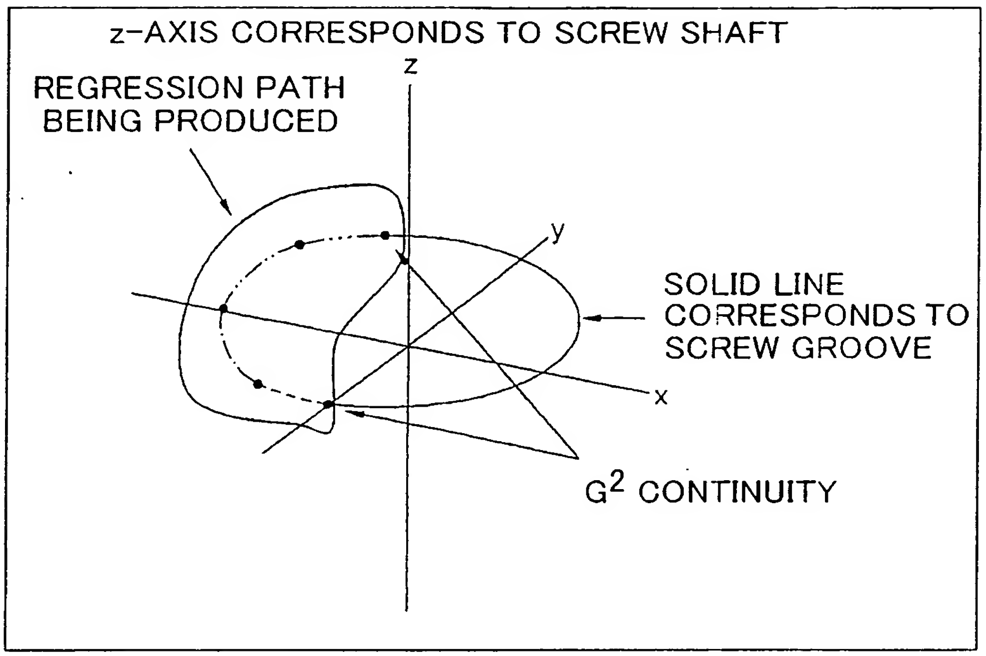

z-AXIS CORRESPONDS TO SCREW SHAFT
z
REGRESSION PATH BEING PRODUCED
y
SOLID LINE CORRESPONDS TO SCREW GROOVE
x
G^2 CONTINUITY

FIG.38

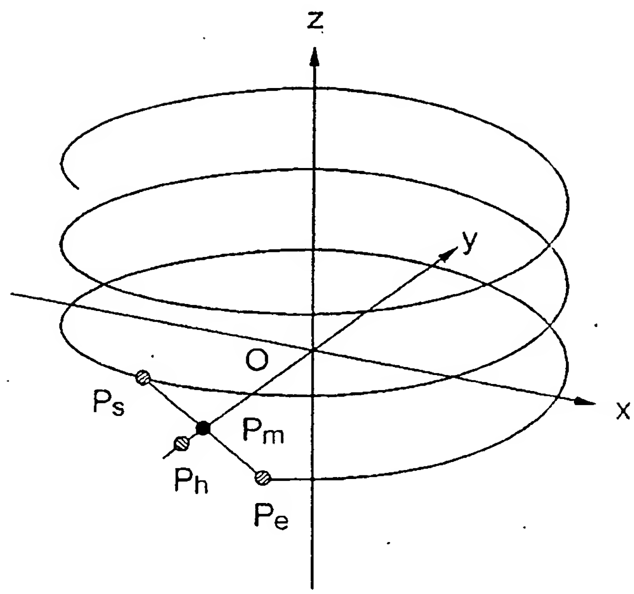


FIG.39

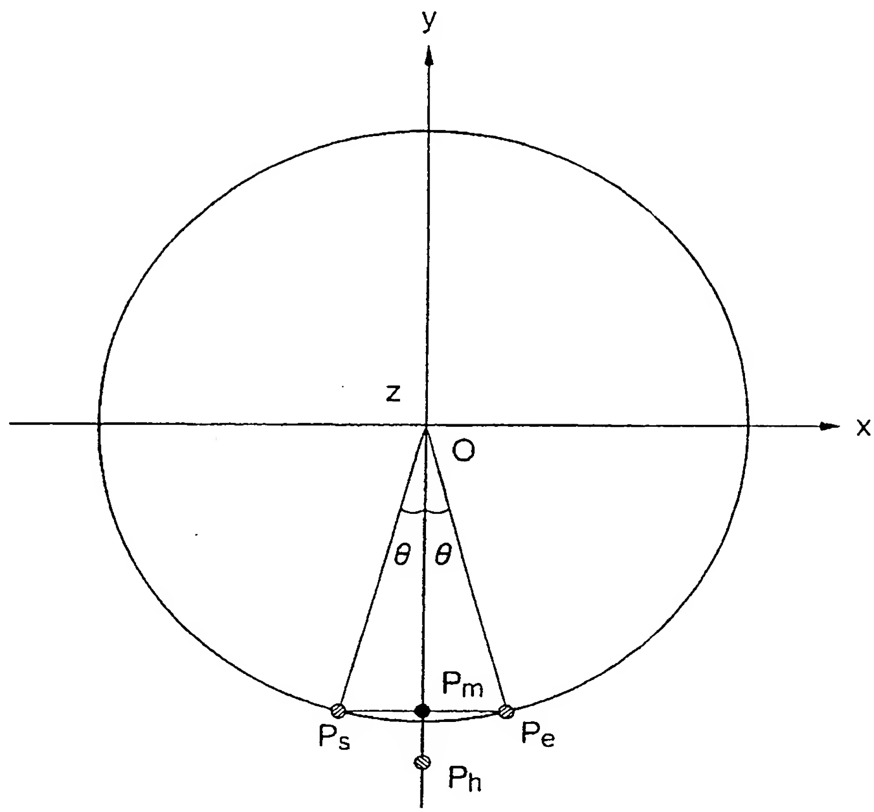


FIG.40

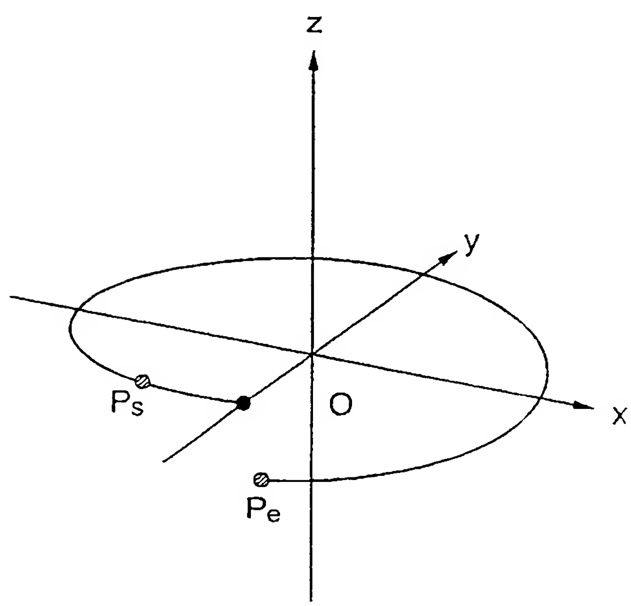


FIG.41

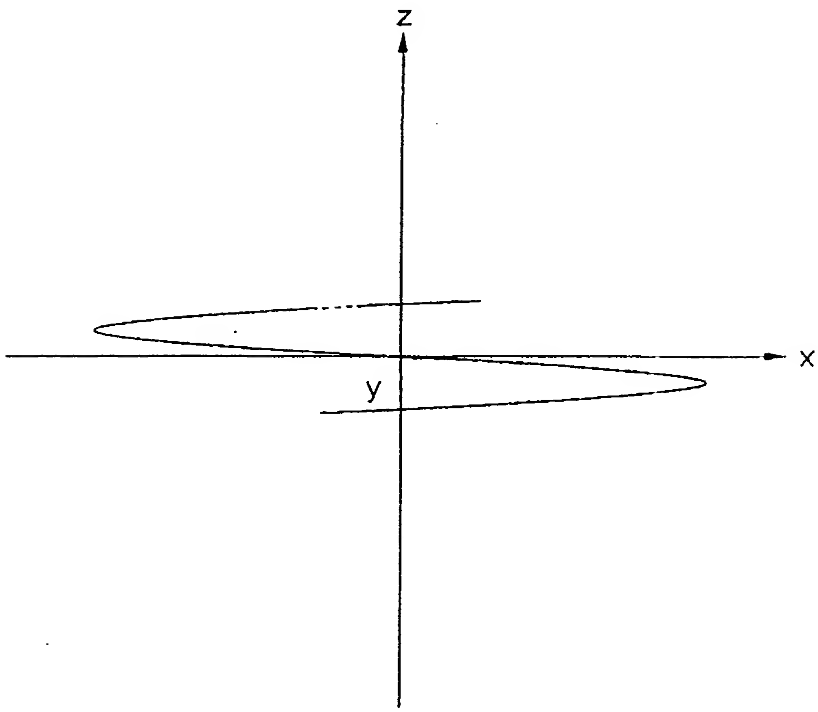
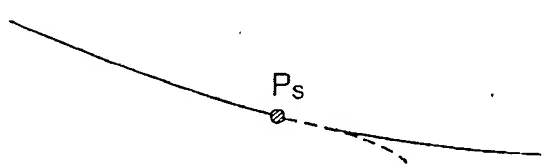


FIG.42



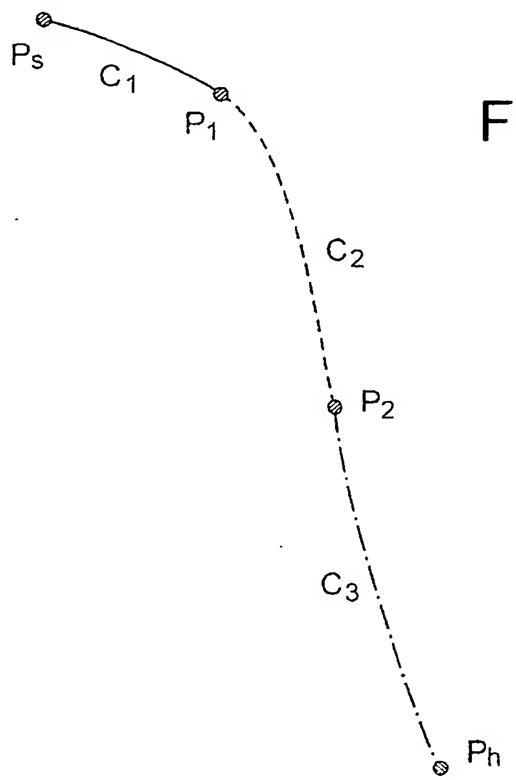


FIG.43

FIG.44

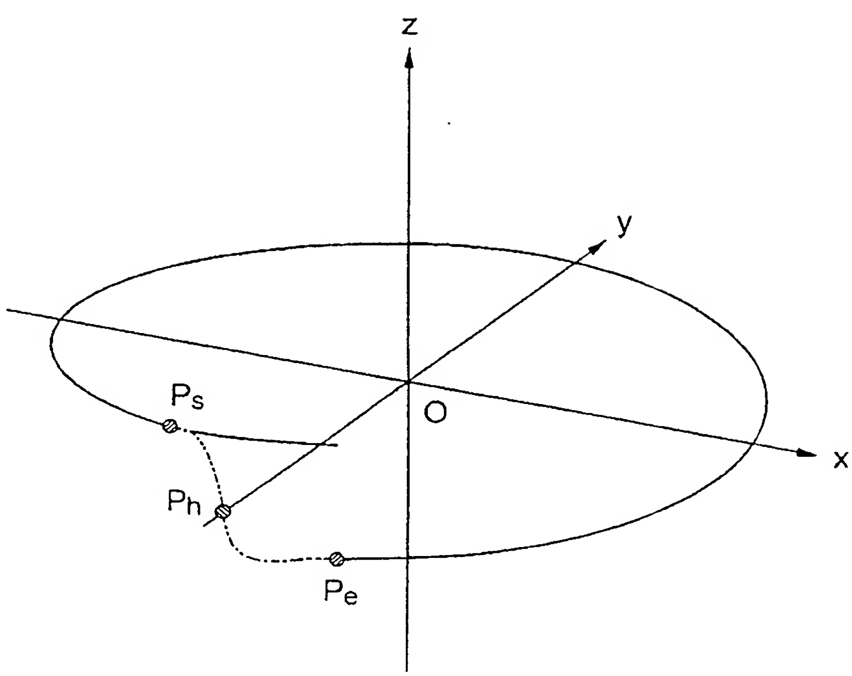


FIG.45

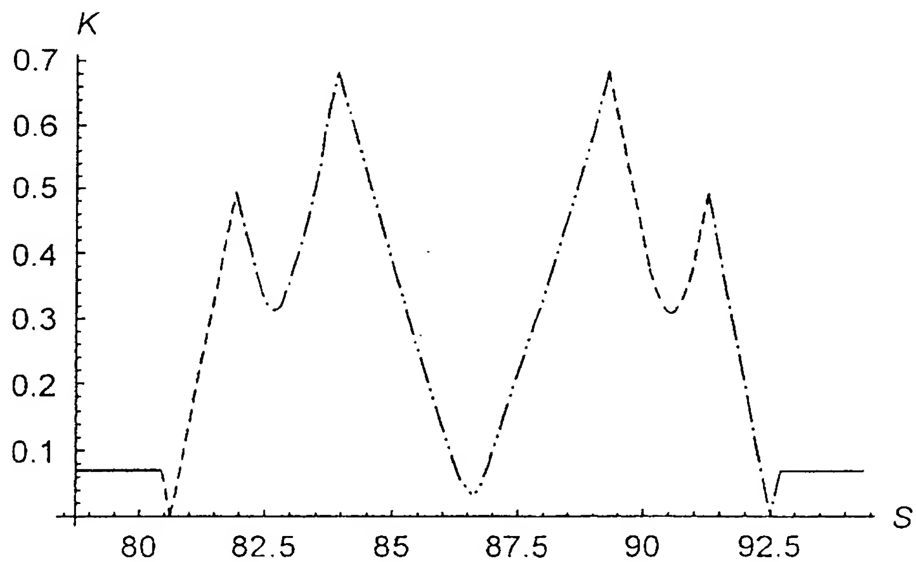


FIG.46

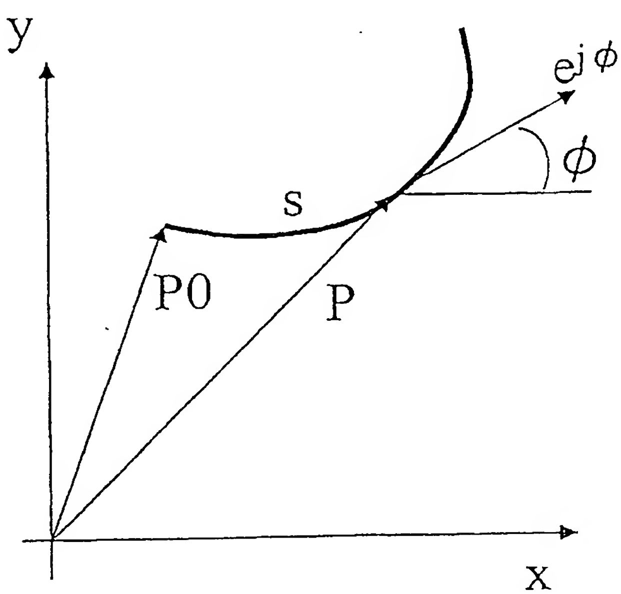


FIG.47

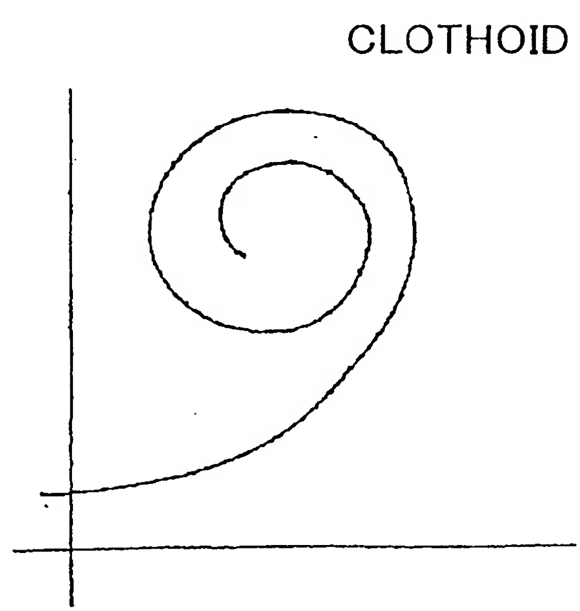


FIG.48

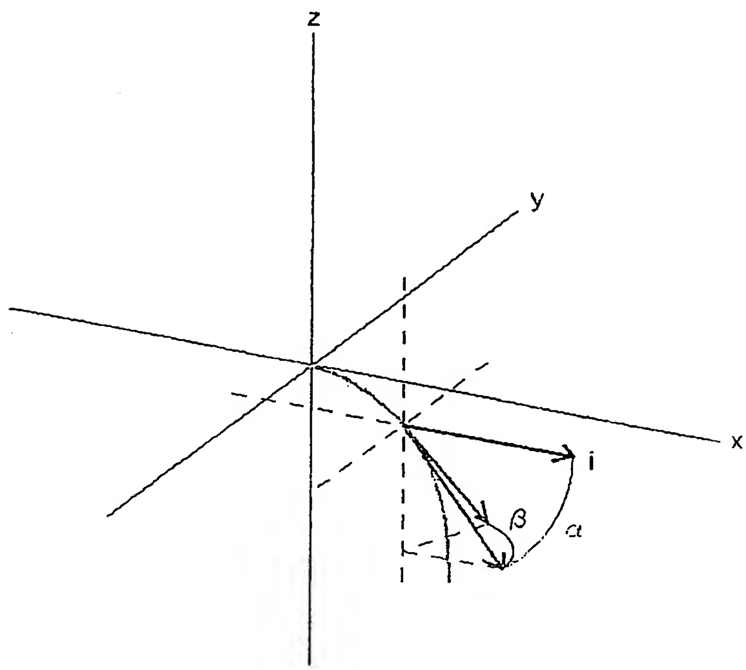


FIG.49

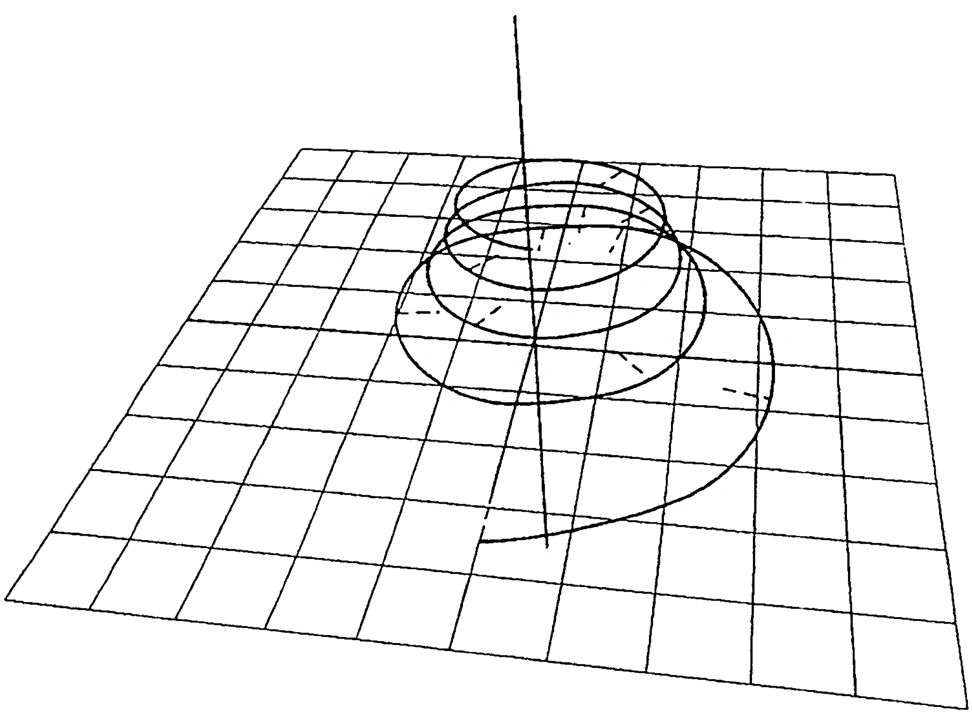


FIG.50

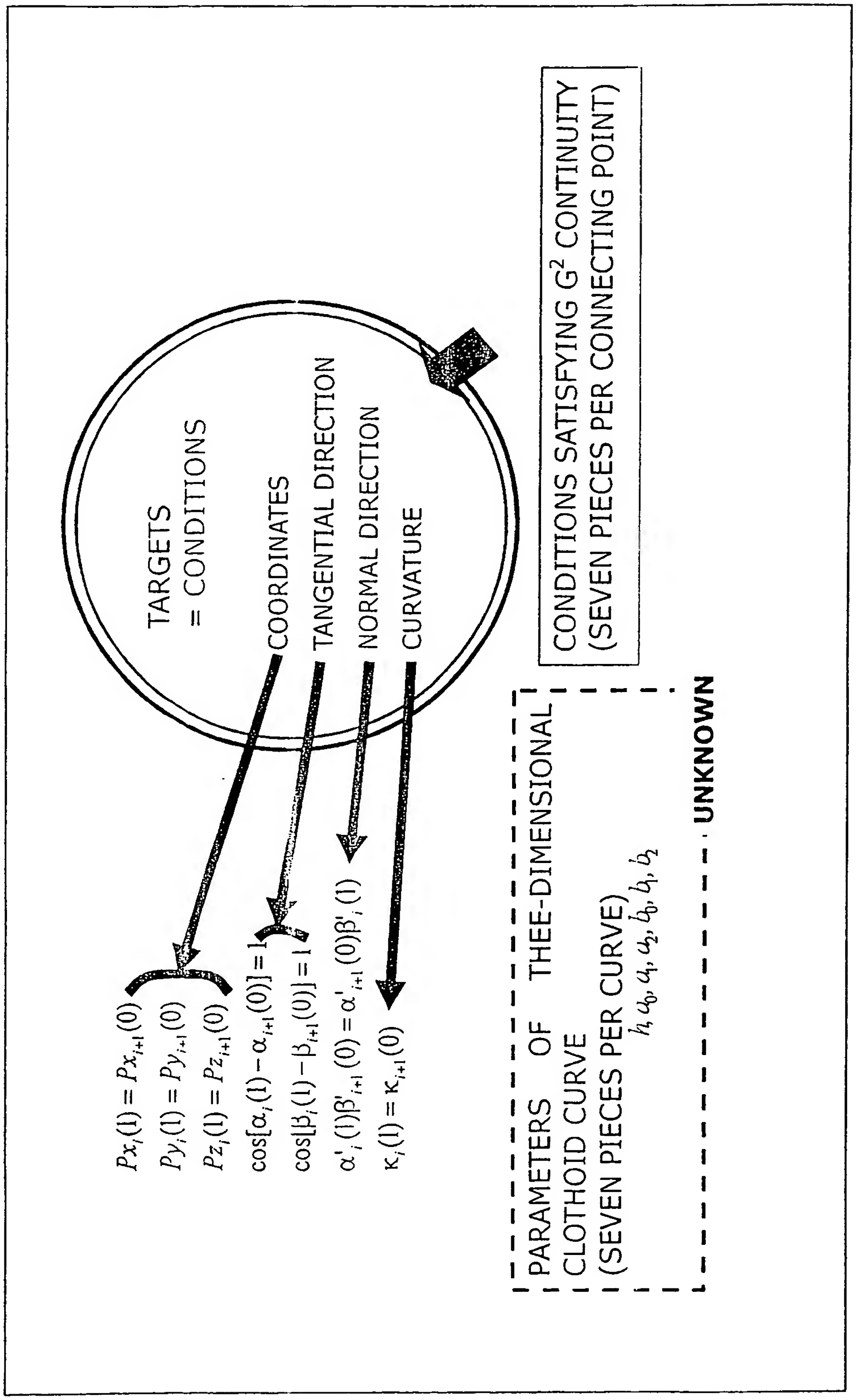

TARGETS
= CONDITIONS
COORDINATES
TANGENTIAL DIRECTION
NORMAL DIRECTION
CURVATURE
$Px_i(1) = Px_{i+1}(0)$
$Py_i(1) = Py_{i+1}(0)$
$Pz_i(1) = Pz_{i+1}(0)$
$\cos[\alpha_i(1) - \alpha_{i+1}(0)] = 1$
$\cos[\beta_i(1) - \beta_{i+1}(0)] = 1$
$\alpha'_i(1)\beta'_{i+1}(0) = \alpha'_{i+1}(0)\beta'_i(1)$
$\kappa_i(1) = \kappa_{i+1}(0)$
CONDITIONS SATISFYING G^2 CONTINUITY
(SEVEN PIECES PER CONNECTING POINT)
PARAMETERS OF THEE-DIMENSIONAL
CLOTHOID CURVE
(SEVEN PIECES PER CURVE)
$h, a_0, a_1, a_2, b_0, b_1, b_2$
UNKNOWN

FIG.51

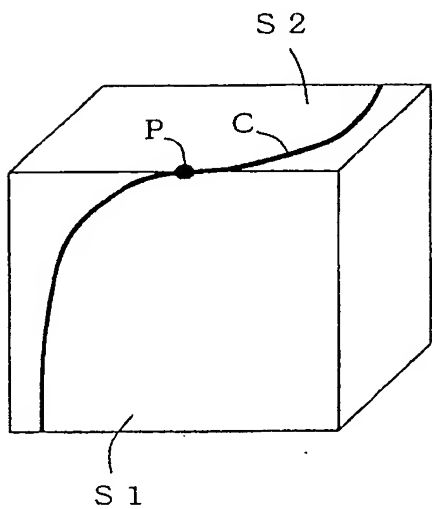


FIG.52

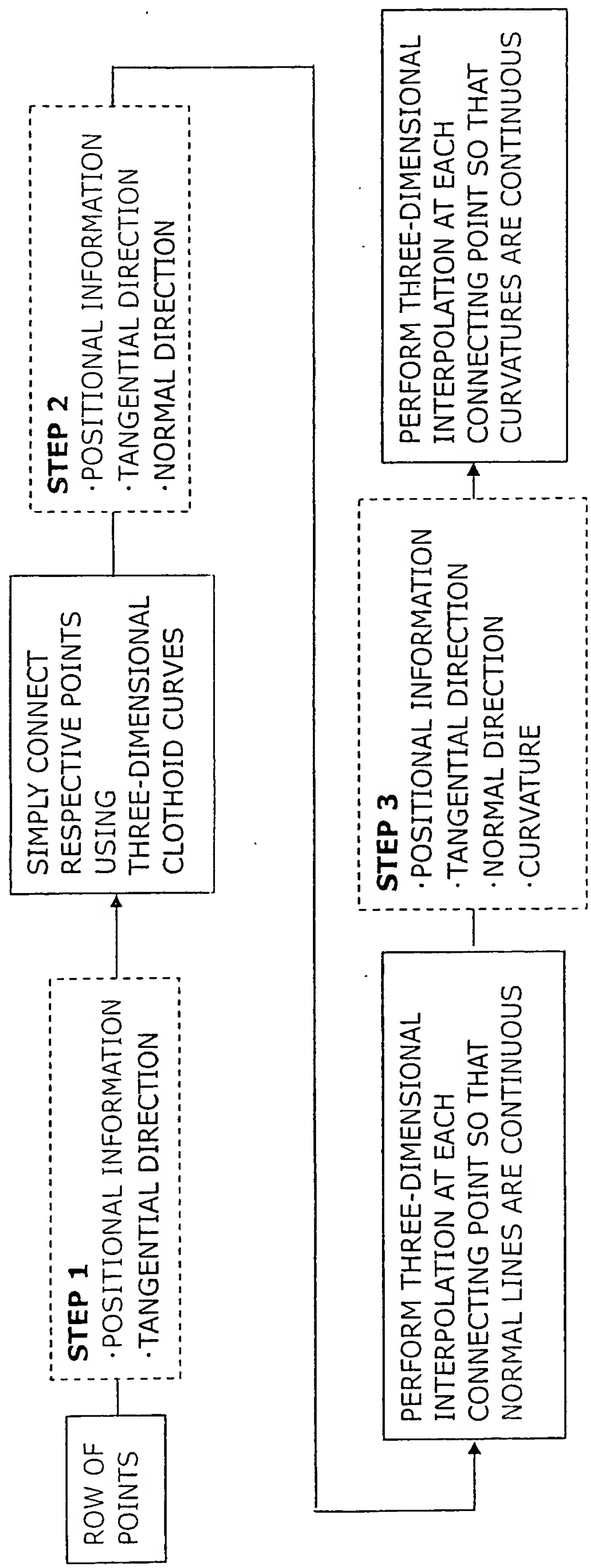

ROW OF POINTS
STEP 1
·POSITIONAL INFORMATION
·TANGENTIAL DIRECTION
SIMPLY CONNECT RESPECTIVE POINTS USING THREE-DIMENSIONAL CLOTHOID CURVES
STEP 2
·POSITIONAL INFORMATION
·TANGENTIAL DIRECTION
·NORMAL DIRECTION
PERFORM THREE-DIMENSIONAL INTERPOLATION AT EACH CONNECTING POINT SO THAT NORMAL LINES ARE CONTINUOUS
STEP 3
·POSITIONAL INFORMATION
·TANGENTIAL DIRECTION
·NORMAL DIRECTION
·CURVATURE
PERFORM THREE-DIMENSIONAL INTERPOLATION AT EACH CONNECTING POINT SO THAT CURVATURES ARE CONTINUOUS

FIG.53

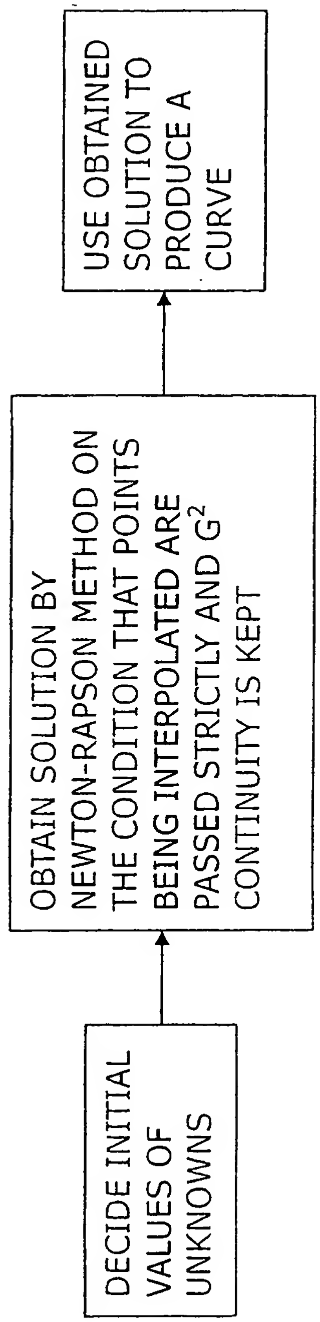

DECIDE INITIAL VALUES OF UNKNOWNS
OBTAIN SOLUTION BY NEWTON-RAPSON METHOD ON THE CONDITION THAT POINTS BEING INTERPOLATED ARE PASSED STRICTLY AND G^2 CONTINUITY IS KEPT
USE OBTAINED SOLUTION TO PRODUCE A CURVE

FIG.54

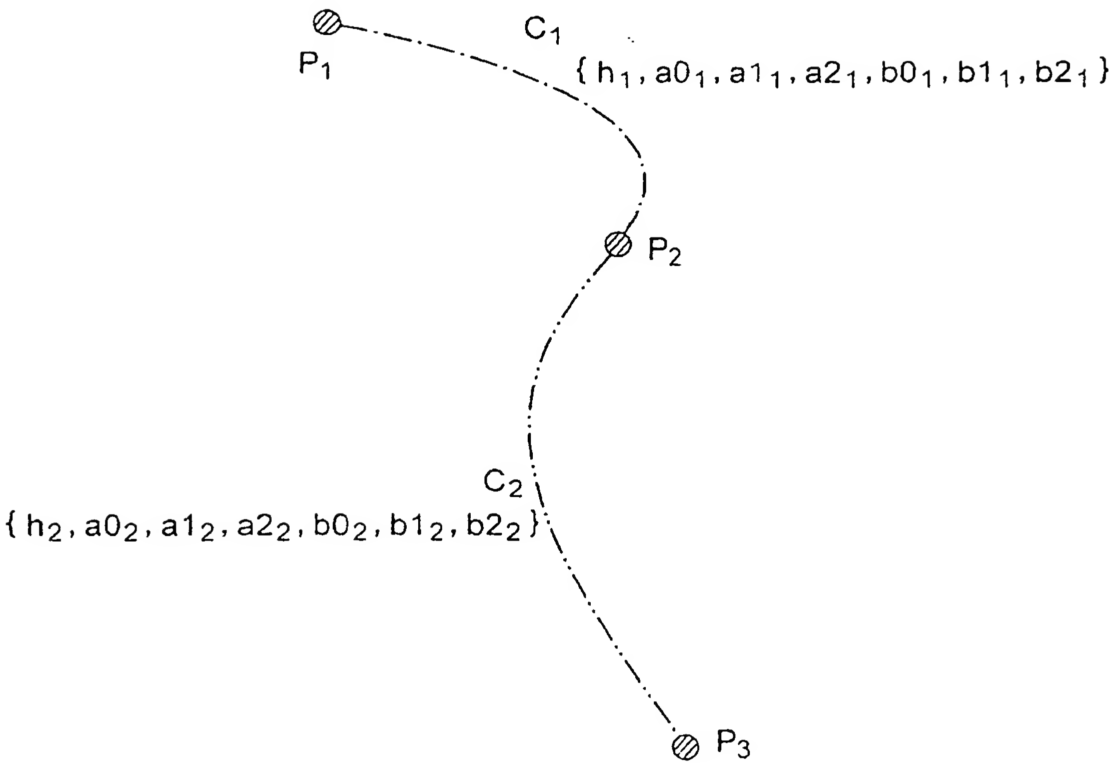

P_1
C_1
$\{h_1, a0_1, a1_1, a2_1, b0_1, b1_1, b2_1\}$
P_2
C_2
$\{h_2, a0_2, a1_2, a2_2, b0_2, b1_2, b2_2\}$
P_3

FIG.55

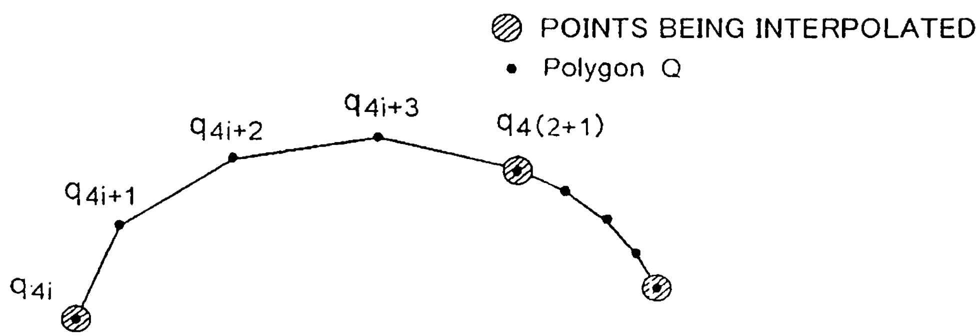
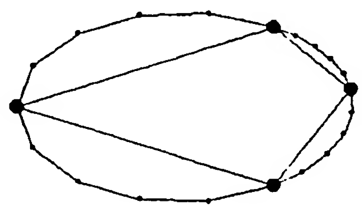

POINTS BEING INTERPOLATED
Polygon Q
q_{4i+3}
q_{4i+2}
$q_{4(2+1)}$
q_{4i+1}
q_{4i}

FIG.56



$$P = \{\mathbf{p}_0, \ldots, \mathbf{p}_{n-1}\}$$

$$Q = \{\mathbf{q}_0, \ldots, \mathbf{q}_{n-1}\}, \qquad P \subset Q$$

● Polygon

P

$$FrenetFrame\{\mathbf{q}_i, \mathbf{t}_i, \mathbf{b}_i, \mathbf{n}_i\}$$

$$\mathbf{t}_i = \frac{\mathbf{q}_{i+1} - \mathbf{q}_{i-1}}{\|\mathbf{q}_{i+1} - \mathbf{q}_{i-1}\|}$$

$$\mathbf{b}_i = \frac{(\mathbf{q}_{i-1} - \mathbf{q}_i) \times (\mathbf{q}_{i+1} - \mathbf{q}_i)}{\|(\mathbf{q}_{i-1} - \mathbf{q}_i) \times (\mathbf{q}_{i+1} - \mathbf{q}_i)\|}$$

$$\mathbf{n}_i = \mathbf{b}_i \times \mathbf{t}_i$$

$$\kappa(q_{i-1}, q_i, q_{i+1}) = \frac{2\|(q_{i+1} - q_i) \times (q_{i-1} - q_i)\|}{|\mathbf{q}_{i+1}\mathbf{q}_i\|\mathbf{q}_{i-1}\mathbf{q}_i\|\mathbf{q}_{i+1}\mathbf{q}_{i-1}|}$$

$$\mathbf{k}_i = \kappa_i \mathbf{b}_i = \frac{2}{\gamma_i}(q_{i+1} - q_i) \times (q_{i-1} - q_i)$$

q: COORDINATE

t : UNIT TANGENTIAL VECTOR

b: UNIT NORMAL VECTOR

n: UNIT ACCESSORY NORMAL VECTOR

k: DISCRET CURVATURE NORMAL VECTOR

FIG.57

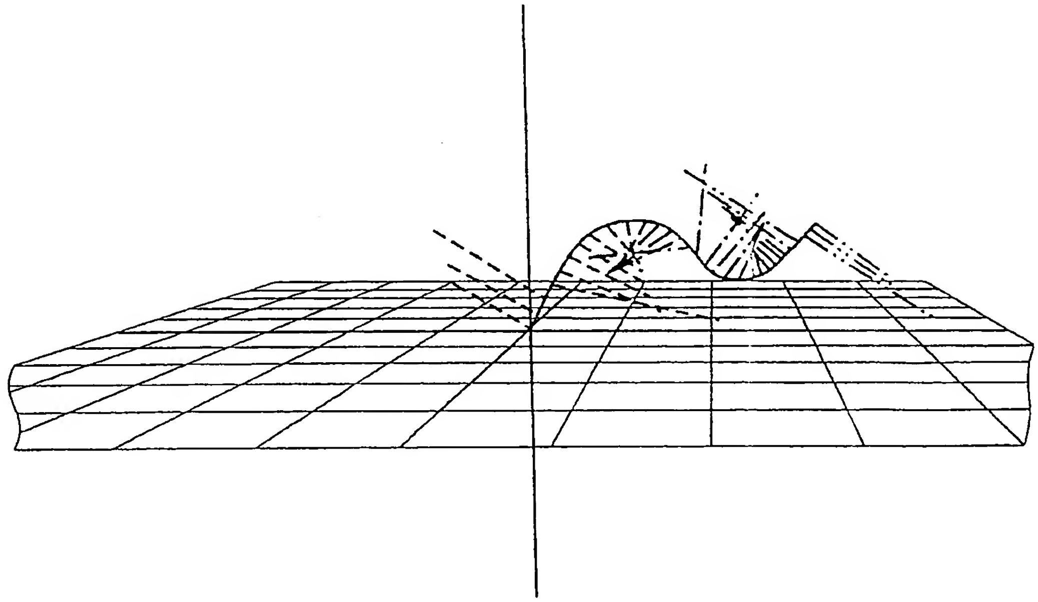


FIG.58

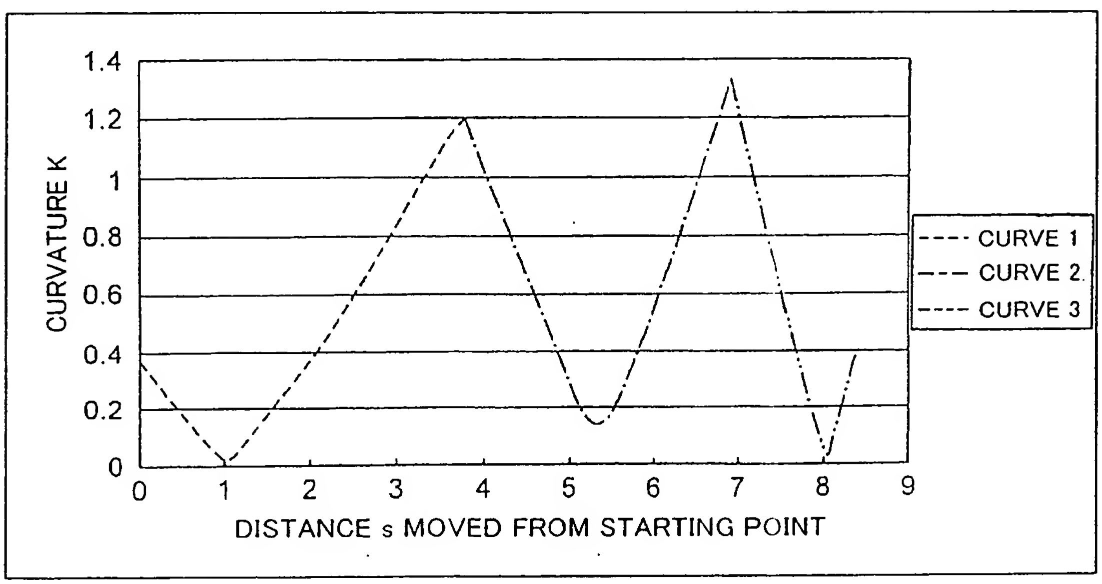

1.4
1.2
1
0.8
0.6
0.4
0.2
0
CURVATURE K
0 1 2 3 4 5 6 7 8 9
DISTANCE s MOVED FROM STARTING POINT
CURVE 1
CURVE 2
CURVE 3

FIG.59

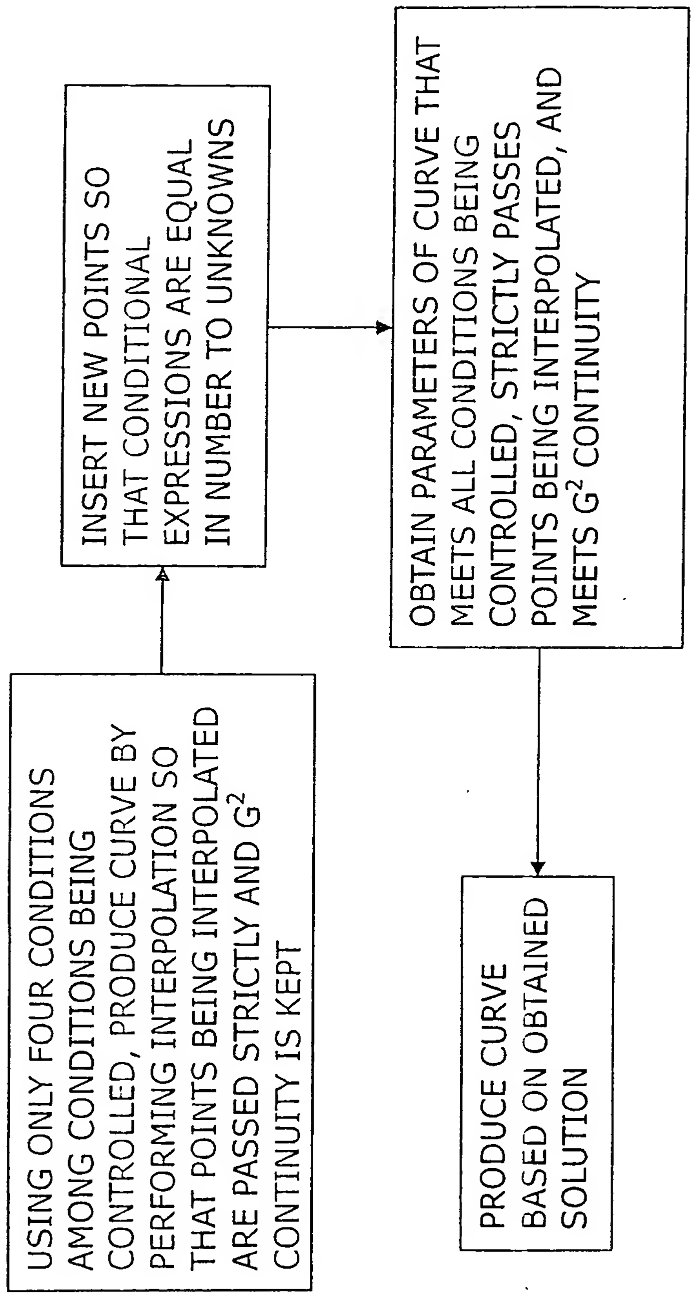

USING ONLY FOUR CONDITIONS AMONG CONDITIONS BEING CONTROLLED, PRODUCE CURVE BY PERFORMING INTERPOLATION SO THAT POINTS BEING INTERPOLATED ARE PASSED STRICTLY AND G2 CONTINUITY IS KEPT
INSERT NEW POINTS SO THAT CONDITIONAL EXPRESSIONS ARE EQUAL IN NUMBER TO UNKNOWNS
OBTAIN PARAMETERS OF CURVE THAT MEETS ALL CONDITIONS BEING CONTROLLED, STRICTLY PASSES POINTS BEING INTERPOLATED, AND MEETS G2 CONTINUITY
PRODUCE CURVE BASED ON OBTAINED SOLUTION

FIG.60

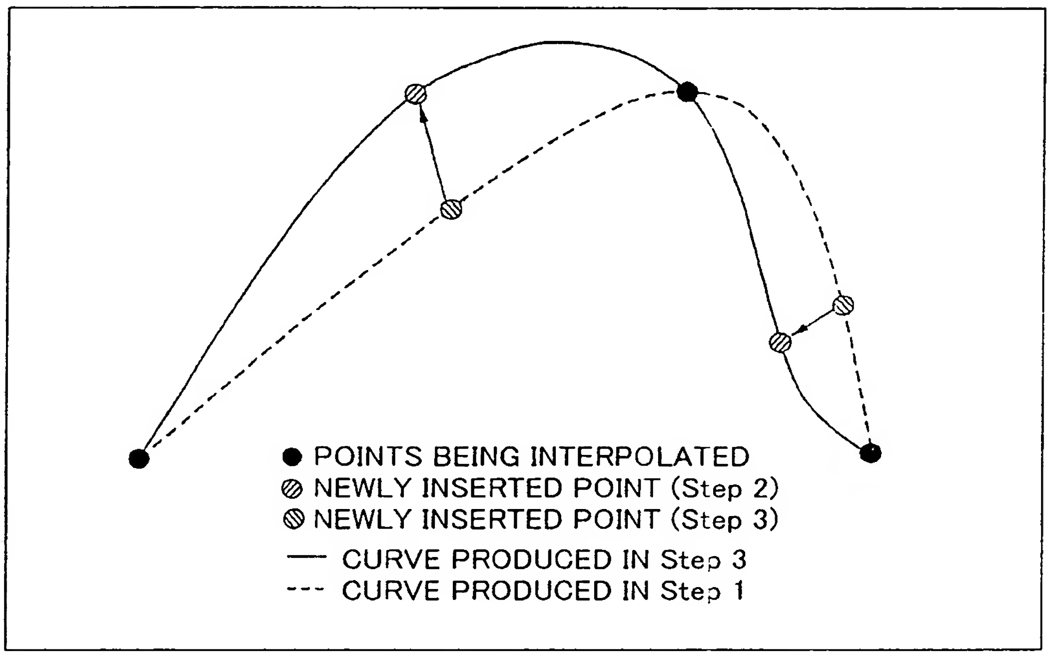

● POINTS BEING INTERPOLATED
NEWLY INSERTED POINT (Step 2)
NEWLY INSERTED POINT (Step 3)
— CURVE PRODUCED IN Step 3
--- CURVE PRODUCED IN Step 1

FIG.61

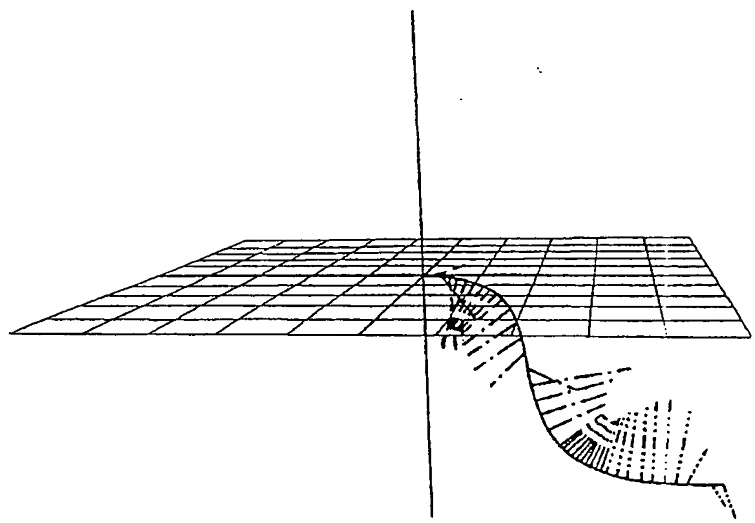


FIG.62

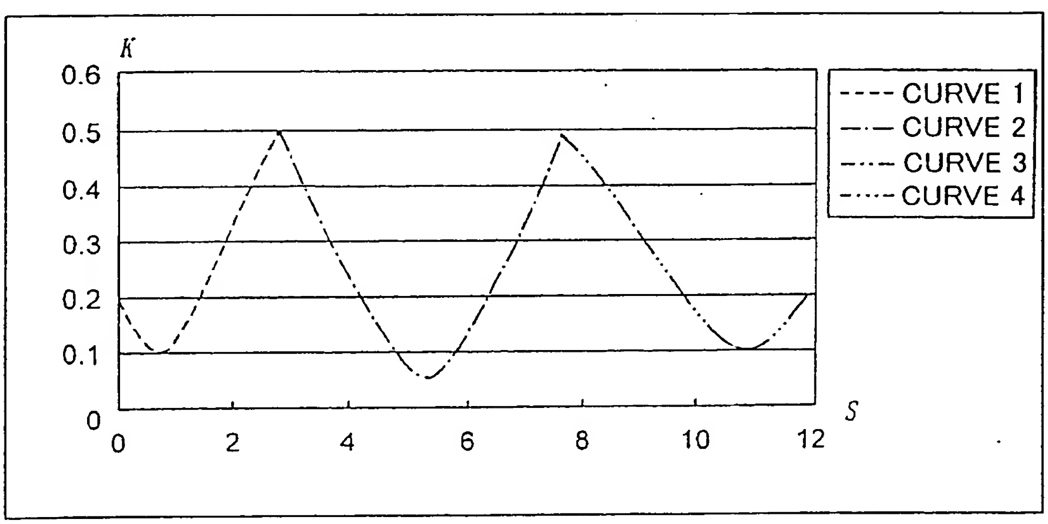


FIG.63

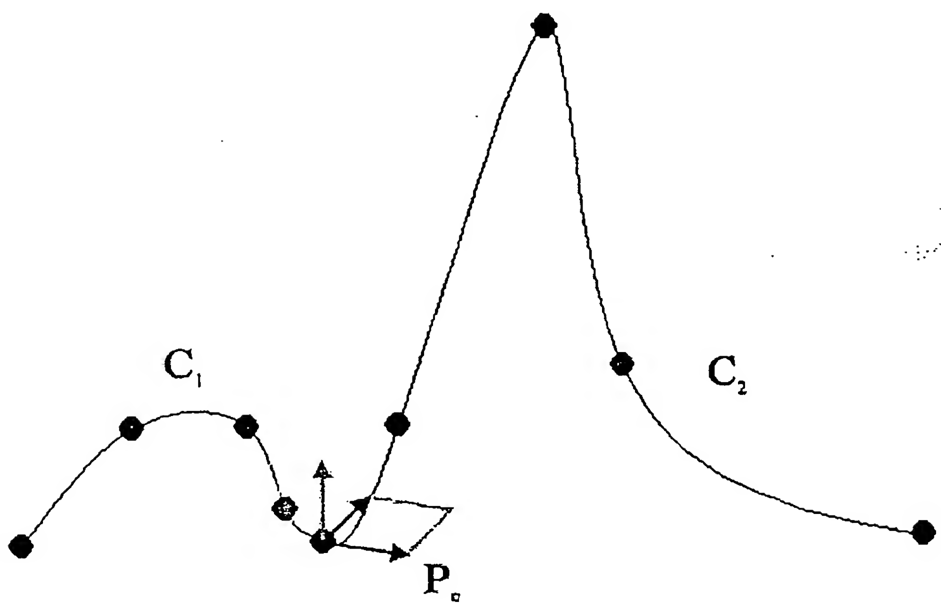


FIG.64

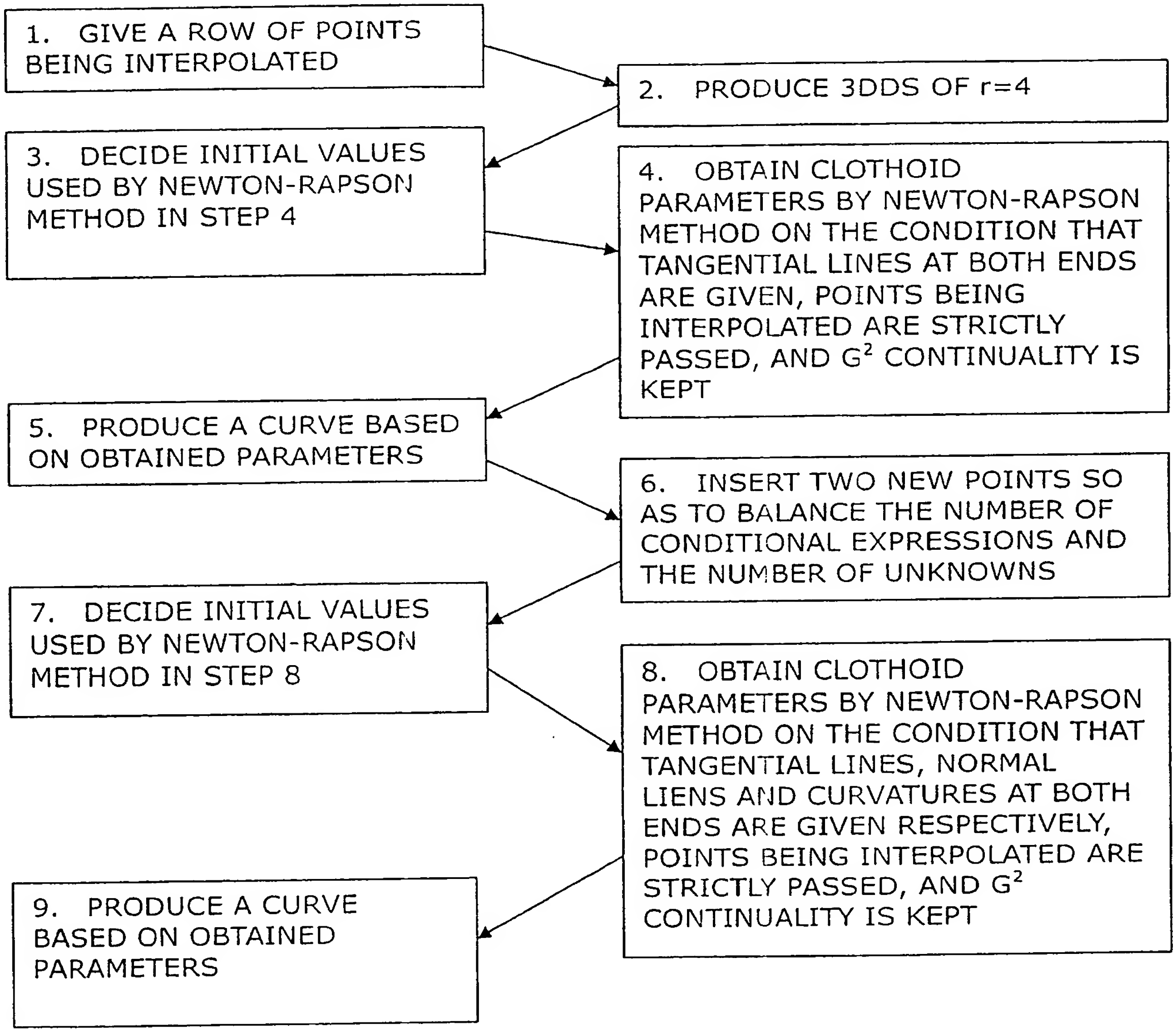

1. GIVE A ROW OF POINTS BEING INTERPOLATED
2. PRODUCE 3DDS OF r=4
3. DECIDE INITIAL VALUES USED BY NEWTON-RAPSON METHOD IN STEP 4
4. OBTAIN CLOTHOID PARAMETERS BY NEWTON-RAPSON METHOD ON THE CONDITION THAT TANGENTIAL LINES AT BOTH ENDS ARE GIVEN, POINTS BEING INTERPOLATED ARE STRICTLY PASSED, AND G^2 CONTINUALITY IS KEPT
5. PRODUCE A CURVE BASED ON OBTAINED PARAMETERS
6. INSERT TWO NEW POINTS SO AS TO BALANCE THE NUMBER OF CONDITIONAL EXPRESSIONS AND THE NUMBER OF UNKNOWNS
7. DECIDE INITIAL VALUES USED BY NEWTON-RAPSON METHOD IN STEP 8
8. OBTAIN CLOTHOID PARAMETERS BY NEWTON-RAPSON METHOD ON THE CONDITION THAT TANGENTIAL LINES, NORMAL LIENS AND CURVATURES AT BOTH ENDS ARE GIVEN RESPECTIVELY, POINTS BEING INTERPOLATED ARE STRICTLY PASSED, AND G^2 CONTINUALITY IS KEPT
9. PRODUCE A CURVE BASED ON OBTAINED PARAMETERS

FIG.65

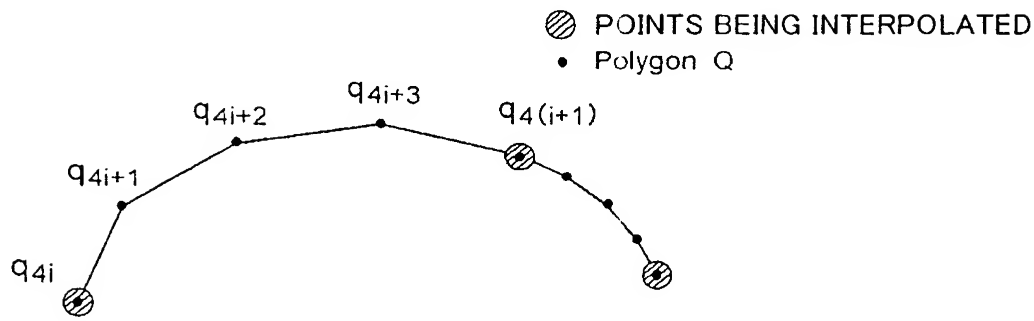

POINTS BEING INTERPOLATED
Polygon Q
q_{4i+3}
q_{4i+2}
$q_{4(i+1)}$
q_{4i+1}
q_{4i}

FIG.66

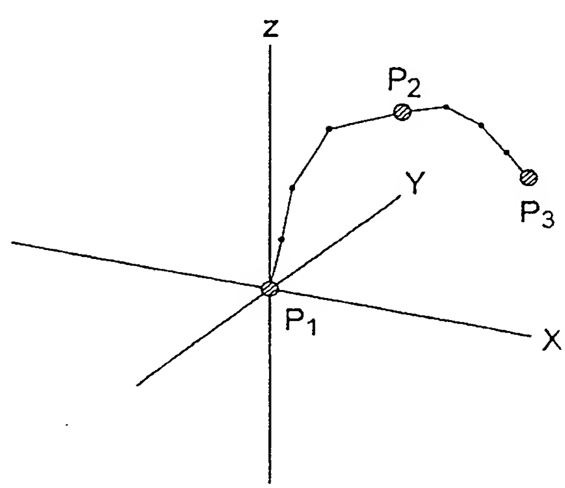

Z
P_2
Y
P_3
P_1
X

FIG.67

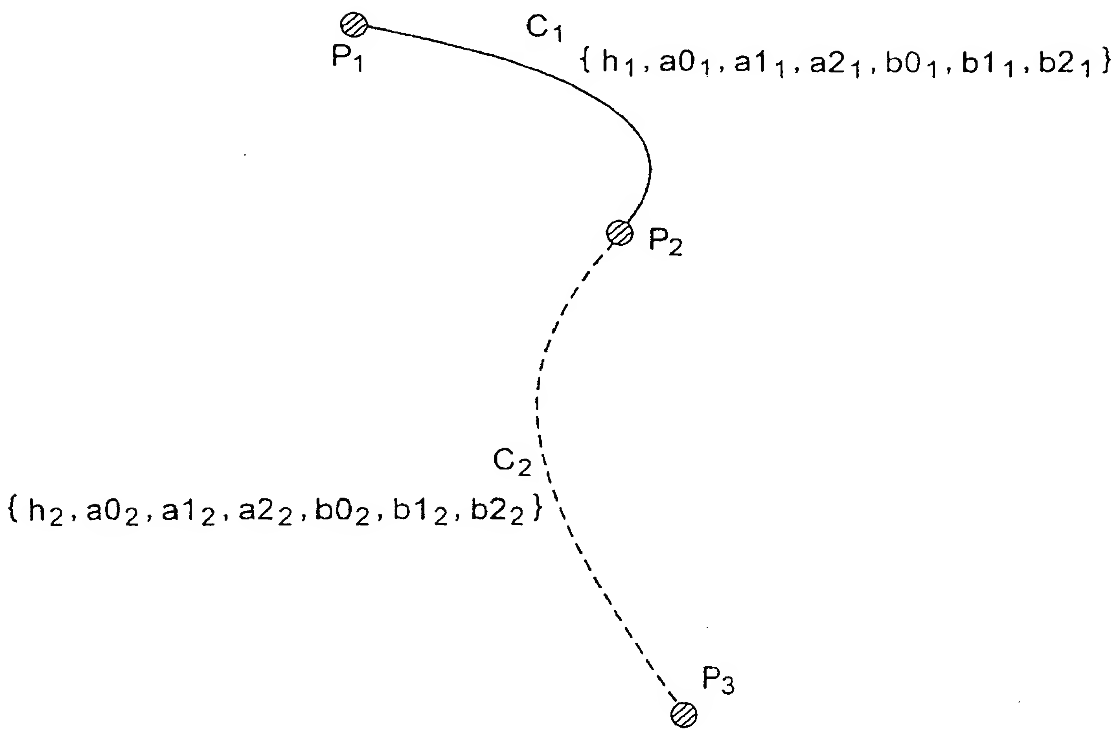

C_1
$\{h_1, a0_1, a1_1, a2_1, b0_1, b1_1, b2_1\}$
P_1
P_2
C_2
$\{h_2, a0_2, a1_2, a2_2, b0_2, b1_2, b2_2\}$
P_3

FIG.68

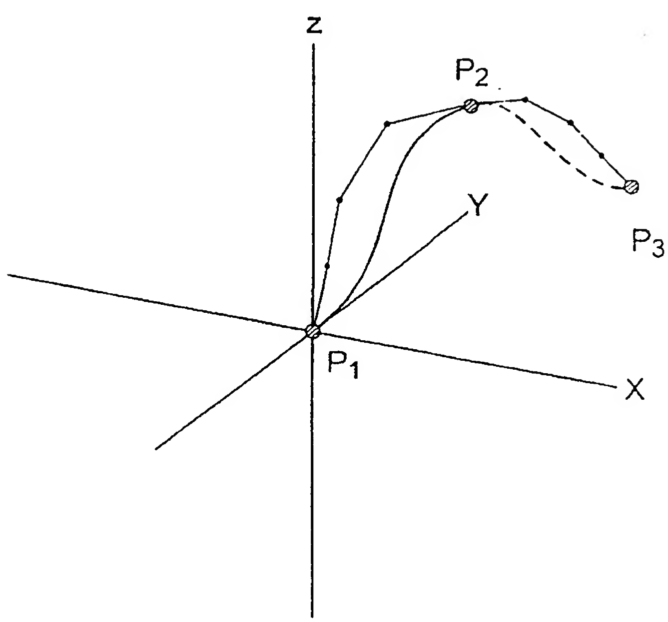

Z
P_2
Y
P_3
P_1
X

FIG.69

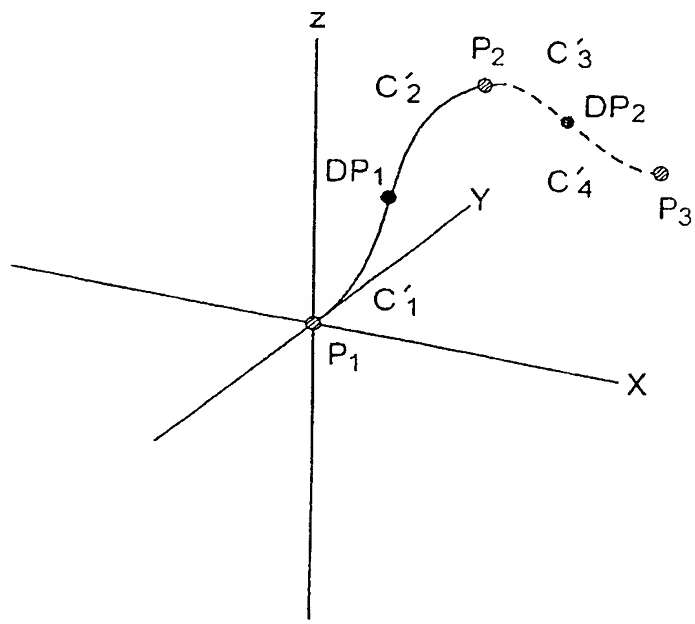


FIG.70

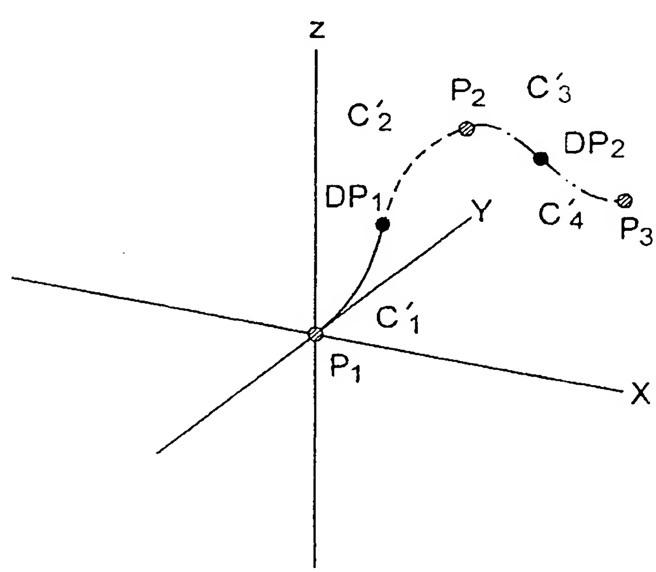


FIG.71

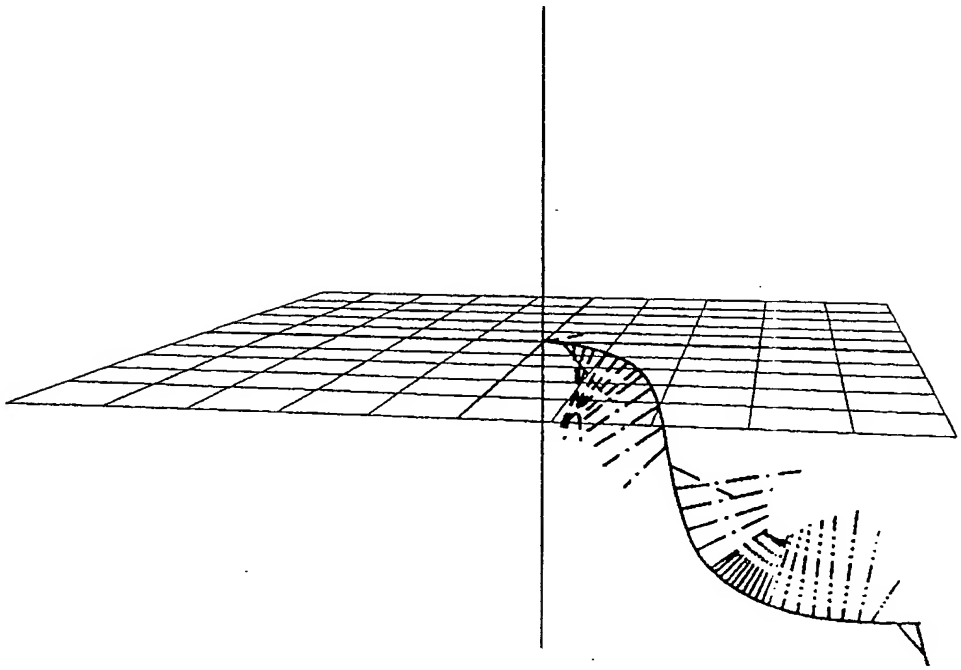


FIG.72

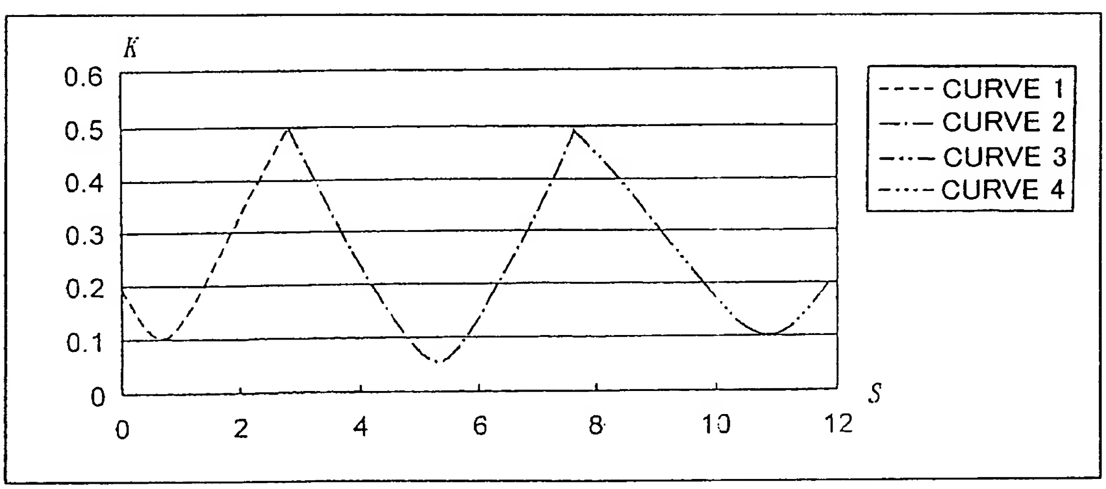


FIG.73

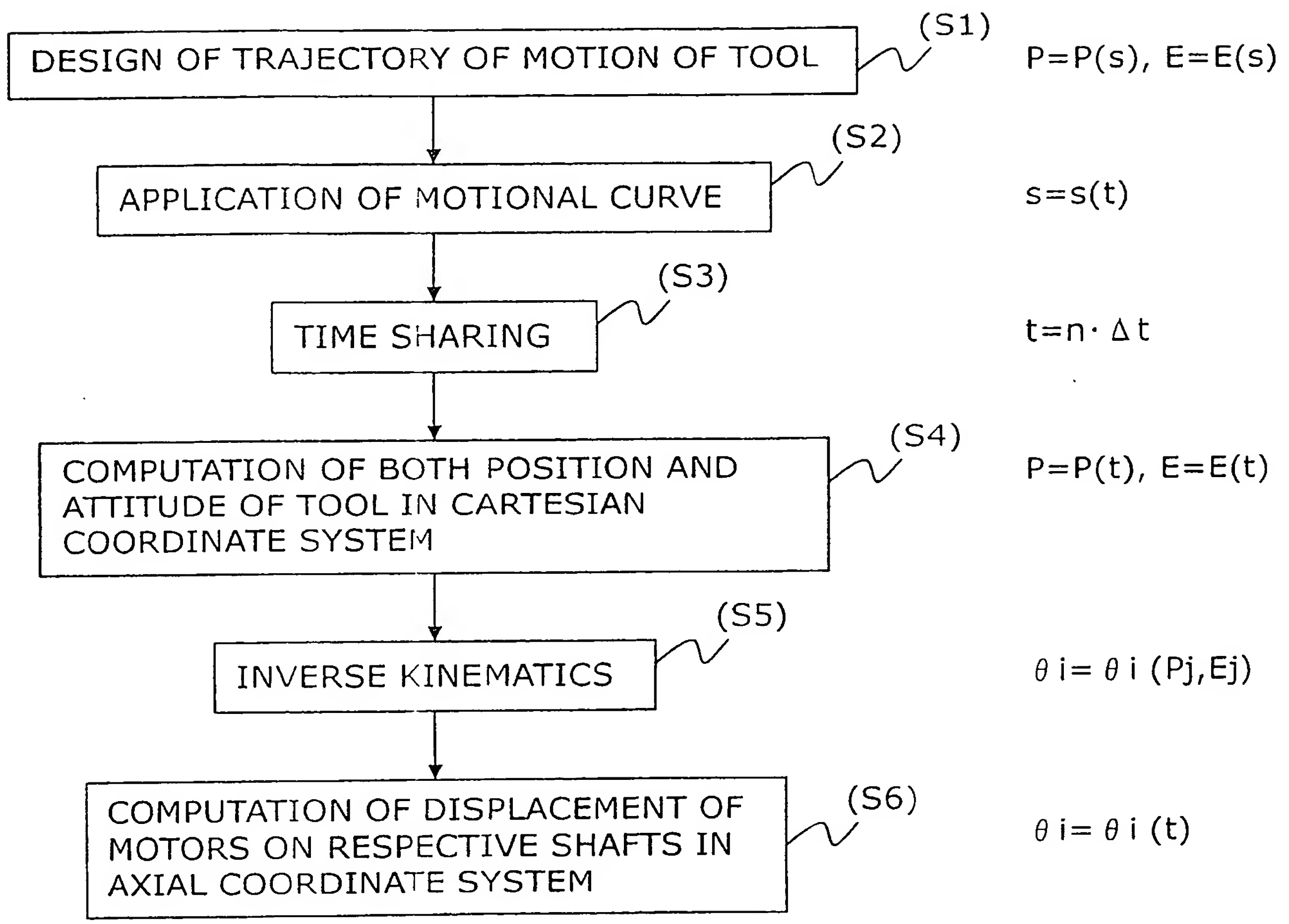

DESIGN OF TRAJECTORY OF MOTION OF TOOL
(S1)
P=P(s), E=E(s)
APPLICATION OF MOTIONAL CURVE
(S2)
s=s(t)
TIME SHARING
(S3)
t=n· Δt
COMPUTATION OF BOTH POSITION AND ATTITUDE OF TOOL IN CARTESIAN COORDINATE SYSTEM
(S4)
P=P(t), E=E(t)
INVERSE KINEMATICS
(S5)
θ i= θ i (Pj,Ej)
COMPUTATION OF DISPLACEMENT OF MOTORS ON RESPECTIVE SHAFTS IN AXIAL COORDINATE SYSTEM
(S6)
θ i= θ i (t)

FIG.74